DIVISION MATERIALS
AND PRODUCTION
CORROSION

Optimal Maintenance of Hot Dip Galvanized Steel

Björn Tidbeck, RISE
Björn Stam, St Control
Bror Sederholm, RISE

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Abstract

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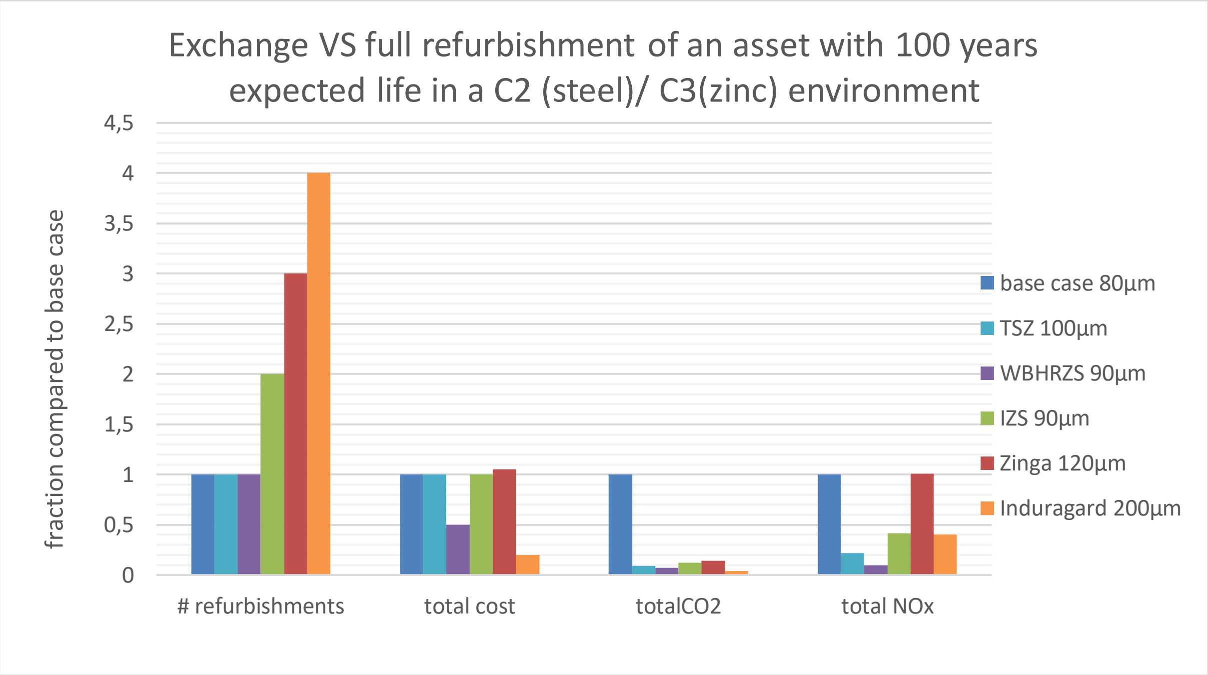

Figure 1 *Summary of estimated total maintenance, cost, climate and NOx footprint for refurbishing a HDG power transmission tower in C2 (steel) C3 (zinc) with an expected service life of 100 years .*

Atmospheric corrosion of HDG coatings are often approximated with general atmospheric corrosion of zinc using corrosivity exposures as per EN-ISO 9226. This approximation is probably good for the initial corrosion rate of a newly produced HDG surface, and with some margin, probably also relevant for the complete HDG layer.

In most well aerated installations, general atmospheric corrosion on zinc is very low, usually about 0,5-2,0 µm per year, (in Sweden). Based on the general corrosivity of zinc, a HDG coating with a thickness of 80 µm should give an expected service life of about 40 to 160 years. In that respect, hot dip galvanizing is probably one of the most long-lived corrosion protection for atmospheric installations.

If the installation is exposed to salt and often damp conditions, the situation may be very different. For instance, at Bohus-Malmön, an exposure station on the west coast of Sweden, the corrosivity of zinc in 2020 was measured to be C3 or 7,6 g/(m^2 * y) on panels exposed to the south at an inclination of 45 degrees, resulting in an expected life of about 80 years for an 80 µm thick HDG coating. At the same location, the corrosivity on panels facing north under an inert rain protection showed a corrosivity of C5 or 35,9 g/(m^2 * y). The corresponding corrosion rate for north facing samples was about 5 µm per year resulting in an expected life of about 16 years for an 80 µm thick HDG coating.

This corrosion behaviour may lead to hot spots of relatively high corrosion on HDG steel structures. It is therefore quite likely that the practical service life of a given HDG steel structure will be dictated by the corrosion rate at hot-spots. A design life approximation based on zinc corrosion rates for well aerated samples exposed in a favourable way, (for instance as described in ISO 9226) may therefore risk to over-appreciate the practical life of a given HDG structure. To find an optimal strategy to prolong the life of HDG steel, it is probably important to find a practical and economically viable way to repair hot spots of corrosion damage on HDG steel.

One common installation where HDG steel might be at risk for galvanic corrosion is where the coated steel members is partially cast in concrete and the HDG steel has come into contact with the reinforcement bars (rebars), galvanic corrosion of this kind can lead to a very quick depletion of the zinc coating and perforation of the underlying steel. Methodology to avoid and prevent such corrosion problems have been described in this report.

Inspecting HDG-steel for corrosion damage is somewhat different from inspecting steel coated with non-metallic protective coatings. Painted steel that has started to rust is relatively easy to spot by examining the steel visually for damage. Corrosion hot-spots, rust spots, flaking, cracking or blistering in an organic coating is usually assessed visually according to the ISO 4628 series. Coating defects of this type will generally constitute weak points in the coating that sooner or later will be accompanied with rusting of the base material. When it comes to HDG steel, the method described in EN ISO 4628 is not ideal. A HDG coating consists of several distinct layers of steel/zinc alloys, typically a HDG coating will consist of up to four Fe/ Zn layers with varying amount of steel content. When the outer zinc layer of a HDG coating has been consumed, the degradation of the coating will continue with consumption of steel/ zinc alloys. The steel alloys give rise to brownish corrosion products that may appear as rust. This type of corrosion is often called alloy corrosion of HDG. Because the steel/zinc alloys also have a good protective effect, any corrosion assessment of HDG-steel must include coating thickness measurements of the coating. To correctly perform thickness measurements of HDG-steel, the coating must be treated by scraping or steel wire brushing to remove any corrosion products that may have built up on top of the HDG coating.

Five different coating systems have been investigated by inspection of reference objects. The emphasis has been on trying to find reference objects that are well documented and that have been coated a long time ago. The study has focused mainly on zinc-rich coatings, with special interest in zinc-rich coatings that have been used as stand-alone systems, i.e. without any topcoat. Such coating systems can increase the applicability and ease of use as repair or refurbishment systems for HDG-steel structures. The references used in the study includes coating systems applied on low alloyed steel. The performance of coatings on steel is important for any coating used to repair HDG-steel. The results from the reference inspections is available in a separate report. [1] Some of the highlights from the report are as follows:

The breakdown mechanism of a coating can be very important when considering the corrosion protection of an asset from a life cycle perspective. It is evident that all the zinc-rich coatings studied deteriorated from the outside and in rather than via under-rusting and flaking. This mode of breakdown can be very advantageous, it means that the assets can be spot repaired to a higher extent than if they were protected with a coating system that deteriorates via flaking and loss of adhesion. A relatively easy and ad hoc maintenance protocol for single layer zinc-rich coating systems can reduce the need for downtime and secondary cost for maintenance of the asset.

Maintenance of HDG steel should be divided into two subcategories, repairs and refurbishment. In this study we have used the term repairs for any treatment of a small damage to the coating of a HDG steel structure. It could be mending mechanical damage due to shipping, correcting surfaces affected by welding or treatment of corrosion hot spots on a relatively small area. A refurbishment of a HDG steel structure would in contrast to repairs treat a larger part of the structure, Typical examples are recoating an old structure with depleted zinc coating or correcting new steel members with a HDG coating with

- **Small damage on new HDG steel**
  - If the corrosivity is low, C3 (for zinc) or lower, small damages can be left unattended provided that they are not located in safety critical areas of the steel structure.

If small damages shall be repaired, any of the following can be recommended:

- Washing, grinding with abrasive paper, brush painting with waterborne zinc silicate
- Washing, blasting to Sa3, and coating with thermally sprayed zinc or Zn/Al

- Washing, blasting to Sa2½, and painting with a zinc-rich coating product

• Refurbishments of complete steel structures

Complete refurbishment of HDG steel structures with worn out corrosion protection may be refurbished by any of the following:

- The Induron method (see section 9.6)
- Wet abrasive blasting followed by painting with vinyl coating
- Wet abrasive blasting followed by painting with zinc-rich coating
- Dry abrasive blasting to Sa3, followed by coating with thermally sprayed zinc or Zn/Al

In this study, three different exposure sites have been selected. Exposure station at Ryda, google coordinates 59.761308, 17.128214. The site can be described as a rural area, the corrosivity is measured annually and is usually C2 for carbon steel and C3 for zinc. Exposure station Bohus-Malmön, google coordinates: 58.325998, 11.316686, can be described as a marine environment, approx. 50m from seashore. The corrosivity is measured annually and is usually C5 for carbon steel and C3 for zinc. Exposure station Borås, highway 40, google coordinates 57.704325, 12.837009, can be described as road environment, the samples are located approximately one meter from the freeway, corrosivity not quantified during this exposure, but previous exposures have indicated a corrosivity of C4 for steel and C4 for zinc along highway 40.

An inspection of the samples exposed at Bohus-Malmön was made on the 22nd of may 2022 after 32 months. Premature coating failure was noted both on Zinga and ZingAlu samples. Coating degradation was found exclusively on the steel side of the flat specimens. The inspection results showed that all other coating systems gave adequate corrosion protection for 32 months in a corrosivity described as C5 for steel and C3 for zinc. At this point, a full destructive assessment of the samples was deemed not meaningful because most samples were virtually unaffected by corrosion. HDG-coatings usually have a very long life span in atmospheric conditions and coating systems used for repairing or refurbishing HDG steel should also have a long life to protect the steel in an optimal way. It is therefore impossible to perform natural corrosion testing of zinc rich coatings within a three year research project. The natural corrosion testing will continue after the project is formally ended. The progress of the sample deterioration will be followed yearly to assess the life span of the coating systems. When enough information has been gained from the corrosion testing the project will perform evaluations of the coating systems and publish the result in a written report containing estimates of the expected service life of the studied methods.
Pretreatment using blasting is a large contributor to the overall environmental footprint. This can be reduced by using laser cleaning to prepare the surface. Laser cleaning also reduces the amount of hazardous waste. The LCA model includes virgin zinc for TSZn and HDG steel. Zinc in coatings may come from zinc dross, recycled from galvanizing plants and many zinc coatings are based on recycled zinc. The zinc origin has a significant factor in the LCA and hence for the resulting environmental footprint. Thermally sprayed Zn and zinc silicates are good options where blasting is possible. Without blasting possibilities, Induraguard 9200 appears to be an interesting alternative. To minimize the NOx emissions, it is important to reduce pretreatment by blasting and to use coating products with low VOC, alternatively to use coating products formulated with VOC with low smog forming potential. Typical solvents that give high smog forming potential are aromatic solvents such as xylene and toluene.

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1 Introduktion på Svenska

Snabba och relativt sett enkla metoder för reparation av varmförzinkade stålkonstruktioner har potential att minska kostnader och effektivisera underhållet för en åldrande infrastruktur. Syftet med detta projekt har varit att undersöka möjligheten att förlänga livslängden på uttjänta och skadade zinkskikt så att den totala kostnaden för reparation eller ombyggnation av varmförzinkade stålkonstruktioner kan minimeras, samt att underhållsåtgärder kan genomföras effektivt och på ett miljömässigt hållbart sätt. Målet med detta projekt är att utveckla metoder för tillståndsbedömning, och ta fram en optimal underhållsmetodik för varmförzinkat stål. Arbetet har baserats på omvärldsanalys, inspektioner av referensobjekt, korrosionsprovning och livscykelanalyser. Föreslagna reparationsmetoder har därmed utvärderas ur teknisk, ekonomisk och miljömässig synvinkel med det övergripande målet att finna en holistiskt optimal underhållsmetodik. Projektet förväntas också ge en objektiv grund för en förändring nuvarande standarder gällande reparation av varmförzinkning.

Arbetet har koordinerats av RISE och utförts inom en arbetsgrupp bestående av: RISE, St Control, Tikkurila Sweden AB, Zinga Sweden AB, Oerlikon Metko, Agaria, IPM Norden AB, Dala zink och Induron. Projektet har finansierats av Svenska kraftnät, Nordic Galvanizers/ European General Galvanizers Association (EGGA), Trafikverket och Infra Sweden 2030 ett forskningsprogram av Vinnova, Formas och Energimyndigheten.

2 Introduction

Fast and relatively simple methods for repairing Hot-Dip Galvanized (HDG) steel structures have the potential to reduce costs and streamline maintenance of aging infrastructure assets. The purpose of this project has been to investigate the possibilities of implementing new maintenance methodologies for HDG steel that could contribute to increased productivity, lowered cost and environmental impact of Swedish infrastructure. The savings are expected to come from life extension of existing infrastructure where rerouting and downtime has a major impact on the total cost estimate for a steel structure replacement. The aim of this project was to propose methods for condition assessment, and to develop an optimal maintenance methodology for hot-dip galvanized steel structures. Proposed repair methods and methods for refurbishment of steel profiles have been evaluated from a technical, economic and environmental point of view in an attempt to find a holistic best practice solution for HDG maintenance.

The work has mainly been performed by RISE AB and St Control AB and is based on corrosion testing, inspections of reference objects, life cycle analysis and state of the art analysis including contacts with asset owners. The project results are expected to provide an objective basis for implementing new maintenance methodologies. The ultimate goal of the project is to extend the life of worn and damaged zinc layers so that the total cost of repair or exchange of old structures can be minimized effectively and in a more environmentally sustainable way.

This project has been led by RISE AB and conducted within a project consortium consisting of: Svenska kraftnät (Swedish powergrids), Nordic Galvanizers/ European General Galvanizers Association (EGGA), Trafikverket (the Swedish road administration), Tikkurila Sweden AB, Zinga Sweden AB, Oerlikon Metko, St Control, Agaria, IPM Norden AB, Dala zink, and Induron. The project has been financed by the project consortium and Infra Sweden 2030, a joint innovation program by Vinnova, Formas and Energimyndigheten.

3 Zinc coatings

Zinc and aluminum are interesting materials when it comes to corrosion protection. These metals benefit from the combination of being less noble than steel while being prone to form oxide layers that effectively reduce the general corrosion of the metal itself. This means that they are consumed slowly. Both Hot Dip Galvanized (HDG) coatings and painted coatings can offer galvanic protection to the underlying steel if there is a damage in the coating. During galvanic protection, the less noble metal is consumed faster than the steel, which results in a concentration reduction of the oxidizing agent, (usually oxygen) and a lower mixed potential of the zinc-steel system compared to a steel surface alone. Both the lower potential and the lower oxygen availability contribute to a relatively slow corrosion of the steel. An intact HDG coating is impermeable to water and oxygen and therefore gives an unparalleled barrier protection compared to painted coatings. Painted or thermally sprayed zinc coatings are often relatively porous. Zinc coatings have the beneficial property of forming slightly basic corrosion products such as zinc hydroxides and zinc carbonates. The basic zinc corrosion products can effectively neutralize the acidic conditions that can develop under a coating as result of anodic delamination. For these reasons, metallic zinc and zinc rich coatings are often the primary choice for mitigating atmospheric corrosion. They are used throughout the world, in industry, infrastructure, and the building sector.

3.1 HDG coatings

It is unclear when HDG started to be used as corrosion protection, but the earliest documented discovery might have been made by the French chemist Melouin in 1742. He described a method to coat steel by dipping it into a bath of molten zinc. The first patent on galvanizing was granted to the Frenchman Sorel in 1836, and the first installation of hot dip galvanized steel is thought to have been ordered by the English navy in 1844. By 1850 galvanizing had become an industry with about 10 000 tonnes of zinc being applied in the UK. [2] In 2017 the estimated world-wide annual zinc production was about 12 million tonnes. Including zinc recycling, the total figure of zinc consumption summed up to about 16 million tonnes. [3] A substantial part of the zinc production is used in various anti-corrosion coatings. For example, in 2009, 55 % of the consumed zinc in the US was used by the galvanizing industry. [4] Today, hot dip galvanizing is one of the most efficient and durable corrosion protection systems known for atmospheric exposures.

Generally speaking hot dip galvanizing is a process that is performed in four steps: Steel components to be galvanized are cleaned and degreased, followed by pickling, fluxing and immersion in a zinc bath at about 460 °C. Normally, steel to be coated does not require pretreatment by abrasive blasting. During the dipping process zinc reacts chemically with the steel to afford a zinc/steel alloy with good adhesion to the steel. Thermally cut edges usually affects the surface composition of the steel resulting in a reduced reactivity between the steel and the zinc. It is therefore recommended that thermally cut edges shall be removed prior to hot dipping. For a successful HDG process, the choice of steel is important. The elemental analysis of the steel affects the thickness, morphology and appearance of the galvanized steel. It is mainly the silicon content of the steel that determines the thickness of the zinc coating. The phosphorus content of the steel also has a certain effect on the reactivity. For aluminum-sealed steels, the sum of the silicon and phosphorus content should be below 0.03 mass%. Within a special range for the sum of the silicon and phosphorus content (0.03 - 0.14% by mass), the reactivity between iron and zinc becomes very high. In this region, a very rapid growth of the layer thickness results in a thick and irregular zinc layer with often impaired adhesion between the steel and the zinc layer. This effect is usually called the Sandelin effect. Hot dip galvanizing imposes certain design criteria on the steel. The steel structure must be designed without hollow members, alternatively, hollow members must be designed with adequate drainage to allow expanding gas and molten zinc to escape from the structure during dipping.

A disadvantage of hot dip galvanizing is that the size of the steel parts to be corrosion protected is limited by the size of the zinc bath. Being an industrialized process, it is impossible to perform hot dip galvanizing in the field on existing steel installations. To maintain or prolong the life of HDG steel one must therefore look for alterative protective coatings that are possible to apply in the field or on-site.

3.2 Thermal spray metallizing

Thermal spray metallizing is a method that enables very large objects to be coated with zinc, aluminum or zinc-aluminum alloys. At the spray gun, a melt of the alloy is formed and applied to the steel structure by means of compressed air. The result is a metal coating usually about 30-300 µm thick. With thermally sprayed zinc, the phase transition between zinc and steel is more well-defined compared with HDG and the adhesion between the steel and the zinc is purely mechanical. The risk of poor adhesion and delamination of the zinc layer may therefore be greater with thermal spraying compared with hot dip galvanizing. Thermally sprayed zinc is also sensitive to pre-treatment of the steel. Generally, abrasive blasting with a cleanliness of at least Sa 2 ½ -Sa 3 and blasting profile medium/ coarse grit is required. There are various types of equipment for thermal spraying. The main types are flame spraying and electric arc spraying. With flame spraying a hot zone in the spray nozzle is created by the combustion of acetylene and oxygen. With electric arc spraying, a high voltage at the nozzle forms a high temperature arc that melts the metal. Electric arc spray metallization is somewhat more effective than flame spraying but the equipment is more expensive and more bulky. Metallization by thermal spraying is noisy and laborious. Risks of inhalation of zinc metal are also present. Spray metallizing is common for coating bridges in Norway. One bridge coating system preferred by the Norwegian road administration (Statens vegvesen) is spray metallized zinc with subsequent organic coatings. An intermediate layer consisting of MIO-pigmented alkyd paint and topcoat with alkyd paint is used. In the reference object study performed within this project, a reference with thermally sprayed Zn/Al 85:15 has been inspected. From the results of that inspection it is clear that thermally sprayed zinc coatings can give a good corrosion protection without top-coat, at least in moderately corrosive environments. This result is also supported by previous investigations. Performed by RISE. [5] Spray metallizing usually provides a very good corrosion protection, but the method is more time consuming than painting. Spray metallizing is one of the repair methods that is standardized as preferred method in the European standard for hot dip galvanized steel. EN ISO 1461.

3.3 Zinc rich coatings

While galvanizing is a very efficient corrosion protection for structures in atmospheric installations, it suffers from the drawback that the size of the steel to be coated must fit into the zinc bath. The size limitation of the hot dip galvanizing process has triggered the development of sprayable zinc-rich coatings that cure at ambient temperatures. But it was not until 1930 that paint formulations including metallic zinc pigmentation started to appear. In Europe, zinc rich coatings made with various organic vehicles such as alkyd-, phenolic-, chlorinated rubber- and acrylic resins were formulated. [6] Almost simultaneously the first inorganic zinc silicates were invented in Australia by Nightingall. In 1940 Nightingall published a paper on “dimetalization” that describes a formulation of zinc silicates for corrosion protection of steel. Nigtingall´s zinc silicate, named Galvanite was a heat cured coating composed of sodium silicate, zinc dust, bicarbonate and red lead. The heat cured inorganic zinc coatings were very effective. Evidence of that include for example the famous Morgan Wyalla pipeline that was coated with Galvanite in 1944. The Galvanite presented an alternative corrosion protection matching that of hot dip galvanizing. However, since the Galvanite was heat cured it suffered similar drawbacks as hot dip galvanizing. The size limit for steel to be coated was limited, in this case by the size of the heat furnace. During the late 1950´s and the early 1960´s the self-cured solvent borne zinc ethyl silicates were first patented. [6] The zinc rich alkoxy silicate coatings are all based on partially hydrolyzed tetra alkoxy siloxane. But during curing they hydrolyze, and the fully cured coating is completely inorganic. The zinc ethyl silicates presented a solution to the size limitation and avoided the impractical post curing. Zinc ethyl silicates became a success and this type of coatings have been used extensively all over the world in all sorts of applications, including steel in demanding environments such as offshore oil platforms, hydro power facilities and in the shipping industry. Today, the zinc ethyl silicates are considered one of the most effective anti-corrosion protection system that the industry has seen. [7] [6] [8] [9]. During the mid-1960´s through to the late 1970`s NASA published a series of patents related to the development of waterborne silicates that cures quickly at ambient temperatures, [9] [10] [11] [12]. The NASA patents describes various inorganic zinc silicates based on high ratio water soluble potassium silicate. The water soluble zinc silicates has proven to be an even more efficient corrosion protection than the zinc ethyl silicates. Studying protective coating specifications from different parts of the world, some trends or cultural differences may be seen. In Europe, zinc rich epoxy coatings are normally used as the standard primer of choice. This fact is realized by consulting the EN ISO 12944-5 standard for protective coatings. In the US, Australia and New Zealand, zinc silicates are more frequently specified. It is well known that zinc silicates tend to give excellent corrosion protection even in very corrosive environments such as C5 or offshore, see **Fel! Hittar inte referenskälla.**. The AS/NZS standard claims that stand-alone zinc silicates may give a corrosion protection matching that of hot dip galvanizing. They are therefore interesting alternatives for repairing HDG-steel.

***Table 1**. Life to first maintenance in years of inorganic zinc silicates (IZS) and hot dip galvanizing coatings from the standard AS/NZS 2312: 2002*

System	**Designation**	**ISO Environment**				
		C3	C4	C5-I	C5-M	Tropical
75 µm IZS	IZS 1, Solvent Borne	10-15	5-10	1-5	2-10	10-15
75 µm IZS	IZS 2, Water borne	25+	15-25	2-5	10-15	25+
125 µm IZS	IZS 2, Water borne	25+	25+	5-10	15-25	25+
Hot Dip Galvanized	HDG 600	25+	15-25	2-5	5-15	25+

3.4 Stand-alone zinc rich coatings

During 1972-1973 NASA carried out an extensive investigation of about 200 different coating systems based on zinc rich coatings, including both organic and inorganic binders. The sample specimens were evaluated after 18 months outdoor exposure at the Kennedy Space Centre. Perhaps the most interesting conclusion from the test was that zinc rich coatings perform better without topcoats. These findings may be relatively old but it supports the idea of using stand-alone zinc rich coatings to maintain damage on HDG steel. As discussed earlier a single layered coating would contribute to the “ease of use” that is important for realizing a quick and effective maintenance methodology. However the study also raises the important questions of the mechanistic reasons to why zinc rich coatings perform worse when overcoated?

Anodic surface area

The perhaps most straight forward way to explain why stand-alone zinc rich coating may give better performance results in corrosion tests is that the anodic/ cathodic area ratio may be much larger for the stand-alone coatings. For topcoated zincs the anodic surface is limited to the cross section of the zinc layer exposed in the vicinity of a scribe or a damage. However, regarding this hypothesis one must consider that the exposure in the NASA study was made with non-scribed Tator plates,

***Figure 2.** Tator sample plates used in the NASA study 96*

Carbonatization

The atmospheric corrosion rate of zinc and zinc rich coatings depends on the time fraction between dry and wet conditions. The initially formed corrosion products on zinc are relatively soluble in water. Provided that the zinc surface is exposed to alternating periods of wet and dry conditions, the initially formed zinc corrosion products reacts with carbon dioxide from the air to form a dense layer of much less soluble zinc carbonate. The zinc carbonate lowers the rate of further corrosion [75] and prevents fresh corrosion products from being removed from the surface.

Therefore, the zinc carbonate formation is an important process for all types of zinc coatings. Top coated zinc coatings may not be exposed to as many alternations between wet and dry conditions, and therefore may not develop zinc carbonates as readily.

Wet time

Most zinc rich coatings are pigmented above the “Critical Pigmentation Volume Concentration” (CPVC). CPVC is the pigment concentration where the pigments are packed as close as possible and the binder is exactly the amount required to fill the space between the pigments. Many zinc rich paints are formulated that way to ensure electrical contact between the zinc pigmentation and the steel substrate, which in turn is a prerequisite for galvanic protection. All organic and inorganic zinc coatings formulated above the CPVC are porous. They are therefore much more susceptible to water uptake compared to barrier coatings. In a porous stand-alone zinc coating, any moisture absorbed into the coating can escape by diffusion across the coating film, followed by desorption from the surface of the coating, see Figure 2. On the other hand, if a topcoated zinc is damaged to the steel, water can penetrate into the porous zinc coating under the topcoat. When the primer underneath the topcoat has become wet, the topcoat may act as a barrier to water exiting the coating. The water in the primer must then diffuse laterally under the topcoat and desorb at the coating defect, see Figure 3. These circumstances account for much longer wet times in corrosion tests with scribed samples of multi layered coating systems based on porous zinc primers. This may also apply to non-scribed samples, when water penetrates through an intact topcoat the water inside the zinc layer will stay there for a relatively long time. Water ingress into topcoated zinc layers is much slower process, but when it eventually happens it results in prolonged wet-times which may invoke irreversible damage on the zinc pigment.

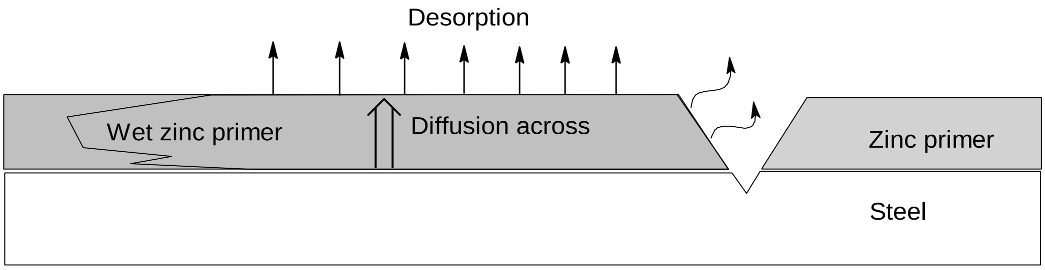

Figure 3 *Drying of a porous stand-alone zinc rich coating. Water diffuse across the coating and desorb from the surface*

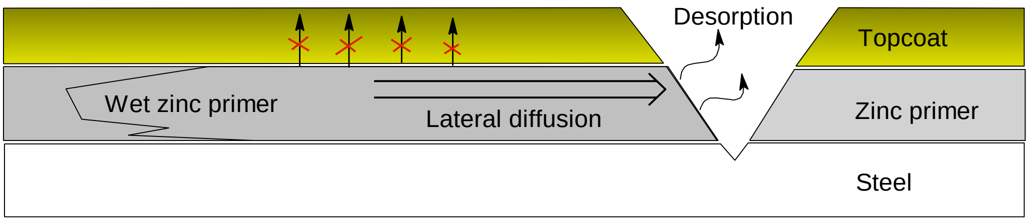

Figure 4 *Drying of a Topcoated zinc rich primer. Water diffuse laterally under the topcoat and desorb from damage in the multilayered coating*

3.5 Barrier type protective coatings

When applying a barrier type coating on top of weathered zinc layers, the pretreatment of the HDG surface is important. One rule of thumb is that barrier coatings should be applied immediately after abrasive blasting, or the weathered zinc substrate should be composed of a sufficiently adhering surface oxide layer. In many instances it may take several years of outdoor exposure for an adequate paintable surface has developed.

Zinc carbonates

With time when zinc or HDG-steel is exposed to weathering, a greyish patina will develop on the zinc. The patina is composed of various zinc corrosion products, mainly zinc carbonate, that has formed as a result of corrosion of the zinc. The corrosion products are slightly basic, has low electrical conductivity and usually adheres quite well to the underlying steel substrate. These properties makes zinc patina a very good protection towards further corrosion and it is in fact the primary reason why zinc is such an important metal for corrosion protection. In order to repair or refurbish an old HDG steel, it is important to decide what to do with the patina. If the coating shall be refurbished with a galvanically protective zinc rich coating, it is of outmost importance that all of the patina is removed prior to overcoating. If the patina is left on the surface, the electrical contact between the zinc in the zinc rich paint and the steel substrate will not be sufficient for the new coating to offer a cathodic protection to the underlying steel. However, with some products, that do not rely on zinc pigment providing cathodic protection to the underlying steel, the porous and tightly adherent patina layer may be utilized to aid adhesion by providing a rough surface of anchoring points. The presence of zinc corrosion products can be assessed with simple contact measurements using a standard multimeter. If there is electrical contact between the electrode and the substrate, a zinc rich coating will have a chance to create a new cathodic protection for the steel substrate. Conversely if after high pressure washing of the substrate there is no contact between the electrode and the base material an insulating patina layer is present on the substrate. The patina layer may have very different roughness characteristics and some surfaces may provide better adhesion than others. It is therefore important to assess the surface profile prior to coating product selection.

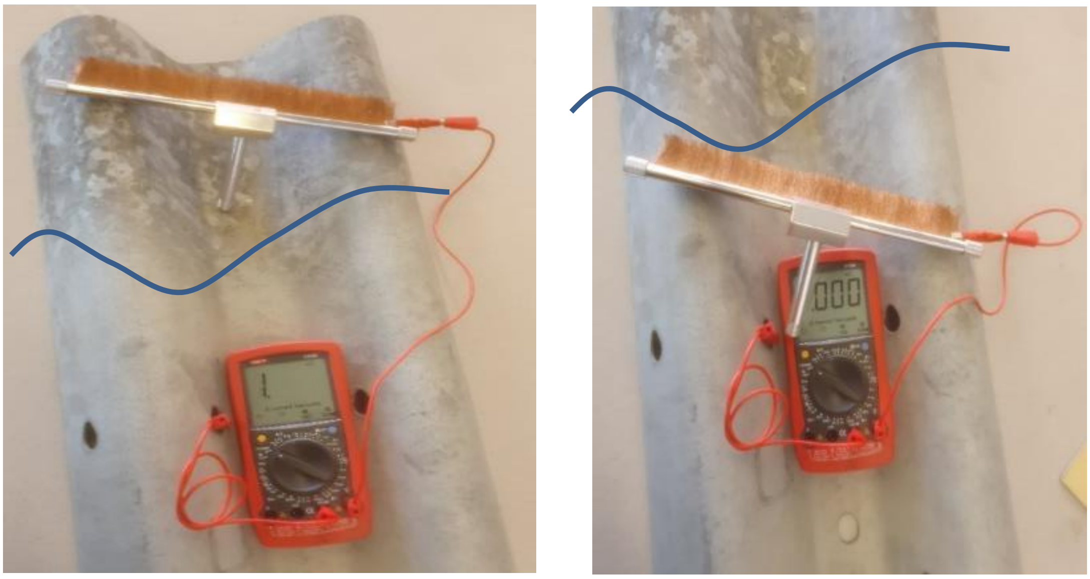

Figure 5. *A HDG steel sheet that has been exposed along a road, the lower part of the sheet, (below the blue line) has been cleaned and pretreated by slurry blasting. The part above the blue line has been washed with fresh water. To the left: no electrical contact with the substrate, (resistance in kΩ- range). To the right: electric contact with the substrate, (resistance in Ω- range).*

4 Damage in HDG coatings

Damage to HDG coatings can be divided into four categories. Damage in connection with the galvanizing process, mechanical damage during transport and installation, wear during the service life of the goods as well as corrosion damage of the HDG steel. Corrosion damage may be subdivided further into general corrosion, galvanic corrosion and stray current corrosion.

4.1 Damage from galvanizing

Examples of damage to the galvanizing layer during the hot-dip galvanizing process includes:

- Stains without zinc layer, also known as "black spots".
- Acid traps
- Inadequate coating thickness

Stains without zinc occur when the steel surface is not wetted by the zinc melt. No zinc coating is then formed on the steel surface. This usually occurs when the steel surface is not sufficiently clean and typical impurities are mill scale residues, welding slag, oils, greases, paints and glue from adhesive tape. In some instances, traces of acid from the pickling pretreatment may reside in small voids or corners where washing after pretreatment has not been effective. This type of imperfection is known as acid traps. Although it might not constitute a damage per say, steel with incorrect alloy composition or heat treated steel can give lower quality that might not meet the specified coating thickness or adhesion of the zinc on for example thermally cut edges.

4.2 Mechanical damage

The most frequent occurring damage is probably mechanical damage during transport and installation. Damage with flaking of zinc layers is often caused by shocks and friction between different parts of the goods during transport and assembly. It is therefore important to pack the goods in a good way and to handle coated steel members with care during assembly. It is also worth mentioning that mechanical damage can be a combined result of poor adhesion and mechanical impact. Although HDG steel should be designed with bolted connections, it is not unusual to see hot dip galvanized steel that has been welded after the galvanization process. All welding of HDG steel should be avoided if possible. The reason to that is manyfold: HDG usually provides adequate corrosion protection in crevices and on sharp edges such as boltheads, in other words, in contrast to painted steel, joining by welding does not provide a better corrosion protection. Zinc may diffuse into the weld and thereby weakening structural integrity and zinc fumes during welding pose a work hazard to welders. Proper repairing of HDG damage is costly and tedious.

Figure 6. *To the left: damage from assembly and inferior zinc adhesion to the steel, the damage may have been avoided with use of proper washers. In the middle: damage from transport, can be avoided with adequate care during handling. To the right: a damage from welding after the galvanization process.*

4.3 General corrosion

As zinc corrodes under atmospheric conditions, a layer of protective zinc corrosion products form on the surface, the protective layer makes the general corrosion slower over time during which the protective layer increase in thickness. For example, a two year corrosivity exposure of zinc will generally show a lower corrosion rate per year compared with a one year corrosivity exposure at the same location. After a certain time, the corrosion of the topmost pure zinc layer on a HDG coating will progress to the underlying Zn/Fe alloy layers. This stage of HDG corrosion is sometimes referred to as alloy corrosion. Alloy corrosion gives a brownish appearance that resembles ordinary red rust. The corrosion rate of HDG with alloy corrosion is however much lower than bare steel. Previous literature studies performed by the Swedish Corrosion Institute [10] show that alloys of Zn/Fe alloys may give similar or lower corrosion rates compared with pure zinc. Atmospheric corrosion of HDG coatings are often approximated with general atmospheric corrosion of zinc using corrosivity exposures as per EN-ISO 9226. This approximation is probably good for the initial corrosion rate of a newly produced HDG surface, and with some margin, probably also relevant for the complete HDG layer. In most well aerated installations, general atmospheric corrosion on zinc is very low, usually about 0,5-2,0 µm per year, (in Sweden). Based on the general corrosivity of zinc, a HDG coating with a thickness of 80 µm should give an expected service life of about 40 to 160 years. In that respect, hot dip galvanizing is probably one of the most long-lived corrosion protection for atmospheric installations. RISE has several field stations for atmospheric corrosion testing, where the corrosivity of steel varies quite dramatically between the different stations from very low corrosivity C2 in sub-arctic conditions to very high corrosivity C5 in marine conditions. [11] However, the corrosivity of zinc at the same exposure sites differs much less, from C2 in subarctic conditions to C3 in marine conditions, see ***Table 2***.

Table 2. *Results from corrosion measurements at different corrosion test sites of RISE.*

Exposure site	Corrosivity steel		Corrosivity category steel	Corrosivity Zinc		Corrosivity category zinc
	g/ m2 y	µm/ y		g/ m2 y	µm/ y	
Gällivare	26	3	C2	3,3	0,5	C2
Ryda	22	3	C2	7,1	1,0	C3
Kattesand	242	31	C3	6,7	0,9	C3
Kvarnvik 3	328	42	C4	8,1	1,1	C3
Kvarnvik west	979	125	C5	7,6	1.1	C3
Brest	750	96	C5	11	1,5	C3
Le croisty	140	18	C2	9	1,3	C3
Dubai	180	23	C2	15	2,1	C3

At Bohus-Malmön, an exposure station on the west coast of Sweden, the corrosivity of zinc in 2020 was measured to be C3 or 7,6 g/(m^2 * y) on panels exposed to the south at an inclination of 45 degrees, resulting in an expected life of about 80 years for an 80 µm thick HDG coating. At the same location, the corrosivity on panels facing north under an inert rain protection showed a corrosivity of C5 or 35,9 g/(m^2 * y). The corresponding corrosion rate for north facing samples was about 5 µm per year resulting in an expected life of about 16 years for an 80 µm thick HDG coating. The corrosion rate can thus be very local and vary quite significantly between different parts of a given steel structure.

Other studies [12] [13]performed by RISE have shown that zinc corrosion can be very high, up to C5 or even higher in road environments, for example, in road tunnels the corrosivity was measured to be up to CX, 9 µm/year. This corrosion behaviour lead to hot spots of relatively high corrosion on HDG steel structures. It is therefore quite likely that the practical service life of a given HDG steel structure will be dictated by the corrosion rate at hot-spots. A design life approximation based on zinc corrosion rates for well aerated samples exposed in a favourable way, (for instance as described in ISO 9226) may therefore risk to over-appreciate the practical life of a given HDG structure. To find an optimal strategy to prolong the life of HDG steel, it is probably important to find a practical and economically viable way to repair hot spots of corrosion damage on HDG steel.

4.4 Galvanic corrosion

Galvanic corrosion can occur when materials of different electrochemical potential are joined together with electrical contact. For galvanic corrosion to occur, an electrolyte that covers both materials but not necessarily the contact point is also required. The electrolyte is usually water or an aqueous solution capable of conducting electric current through ion migration. In a galvanic cell, the more noble metal becomes cathode and catalyzes the oxygen reduction and the less noble metal becomes anode and is attacked by metal dissolution. Whether a material is noble or not is determined by its corrosion potential. A noble metal has a relatively high corrosion potential, while an anodic material has a relatively low corrosion potential. The corrosion potential of a metal depends on both the metal and the corrosion medium. The same metal may therefore have different corrosion potential in different media and it is common to compile and compare the corrosion potentials of different metals into galvanic voltage series.

In the zinc/ steel system of a damaged HDG steel structure, the zinc coating will have a lower potential than the structural steel exposed in the damage. This results in a comparatively fast corrosion of the zinc but a relatively slow corrosion of the steel. During galvanic corrosion the metal oxidation takes place where the electrical resistance to charge transfer and ion conduction is low, this often results in very local damage from galvanic corrosion. Galvanic corrosion can therefore be very serious and corrosion hot spots can significantly limit the service life of a given HDG structure. For galvanic corrosion in submerged conditions there are some general factors that can be taken into account when assessing the risk of galvanic corrosion:

- The corrosion potentials of the metals in a relevant electrolyte
- The ratio between anode and cathode surface area that is wet by the electrolyte
- The conductivity of the electrolyte
- The agitation or flow characteristics of the electrolyte
- The abundance of oxidants in the electrolyte

The biggest impact of these three factors is often the potential difference between the different metals. The greater the potential difference, the greater the risk for galvanic corrosion. If the potential difference is less than 50 mV, the galvanic corrosion can be neglected for most practical applications. Galvanic atmospheric corrosion differs from galvanic corrosion in aqueous solutions in that the electrolyte consists of a thin moisture film. Because of this, it is impossible to establish a galvanic voltage series for metals under atmospheric conditions. Since the corrosion takes place under a thin liquid film, the electrical conductivity of the electrolyte is relatively low. This results in that the area ratio between the anode and the cathode surface is of lower importance in atmospheric galvanic corrosion compared with galvanic corrosion in submerged conditions. It is also the reason why galvanic corrosion on atmospheric structures is typically very local and centered close to the point of electrical contact between the different materials. With atmospheric galvanic corrosion, the time of wetness of the structure and the geometric design of the steel become important.

4.4.1 Galvanic corrosion of cast-in HDG steel

One common installation where HDG steel might be at risk for galvanic corrosion is where the coated steel members is partially cast in concrete and the HDG steel has come into contact with the reinforcement bars (rebars). Cast-in rebars of steel with intact mill scale usually have a corrosion potential of about -100 to -200 mV relative Cu/ $CuSO_4$. Whereas zinc in an aqueous solution usually have a corrosion potential of about -1100 mV relative Cu/ $CuSO_4$. The potential difference is about 1000 mV and galvanic corrosion of this kind can lead to a very quick depletion of the zinc coating and perforation of the underlying steel. Apart from the big difference in corrosion potential, the galvanic corrosion in such cases is often also driven by a very small ratio between the area of the anodic zinc at the concrete interface and a relatively large surface area of the rebars acting as a cathode. Figure 6 shows a typical corrosion appearance of a hot-dip galvanized railing post in contact with the rebars after about two years of exposure in a road environment. The fact that the corrosion damage to the railing posts was concentrated on the lower parts of the railing posts is due time of wetness. Other hot-dip galvanized structures with risk of premature failure due to galvanic corrosion includes: partially cast-in anchor bolts for power line posts in concrete foundations, railing posts in livestock stables and overhead contact posts in concrete foundations for railways.

Figure 7. *To the left: a HDG railing post cast into concrete about two years after installation, the railing post was found to be in electrical contact with the cast-in rebars. In the middle: a painted railing post with galvanic corrosion between the post and the cast-in rebars. To the right. A concrete slab with two protruding ventilation pipes in HDG steel. The left pipe showed red rust at the interface between concrete and steel. The right pipe showed no corrosion at the concrete steel interface. It is probable that the left pipe is electrically connected to the rebars and the right pipe is not. Electrical contact measurement of this particular installation could have avoided this type of corrosion damage.*

4.5 Stray current corrosion on HDG steel

Stray current corrosion can be a very big problem where steel or HDG steel is installed near power transmission cables in connection with for example docks or direct current powered trams. Problems with stray currents usually arise with direct current transmission and is much less pronounced with alternating current transmission. Corrosion problems arising from stray currents should preferably be solved by elimination the stray current and is therefore outside of the scope od this study.

5 Standards for HDG coatings

5.1 *ISO 1461* -Hot dip galvanized coatings on fabricated iron and steel articles – Specifications and test methods

This standard includes requirements and specifications of how and when HDG steel shall be tested for quality control. The thickness of the coating is of high importance and will reflect the life of the coating. The standard stipulates a minimum required coating thickness that depends on the steel thickness. A National Swedish addendum with higher coating thicknesses is present in informative Annex NA of SS-EN ISO 1461. Any requirement specification should clearly specify if Annex NA shall be followed. Thickness measurements shall be performed in accordance with ISO 2808 or ISO 2178. Generally, HDG coatings are used for corrosion protection and the visual appearance of dipped steel is not included in the standard. However, Flux residues lumps and zinc ash is not permitted. The standard also includes requirements of how much damage to the coating that is acceptable and how it shall be repaired. Below are two requirements of the standard that describe damage repairs:

> ***ISO 1461: 2009 6.3 Renovation***
>
> *The total uncoated areas for renovation by the galvanizer shall not exceed 0,5 % of the total surface area of the component. Each uncoated area for renovation shall not exceed 10 cm2. If uncoated areas are larger, the article containing such areas shall be regalvanized, unless otherwise agreed between the purchaser and the galvanizer.*
>
> *Renovation shall be by thermal zinc spraying (for example ISO 2063 [2]) or by a suitable zinc-rich paint where the zinc dust pigment conforms to ISO 3549 within the practical limits of such systems, or by suitable zincflake or zinc-paste products. The use of a zinc alloy stick is also possible (see Annex C).*

Regalvanization may be a good solution for goods that have not yet left the galvanizer. However, if the goods have been transported and assembled,

it is often not practical to blast the steel and perform a regalvanization. For such instances a more efficient repair method may be wanted. Repair using thermally sprayed zinc is a good option but it requires blasting and can be impractical for some installations or building sites. This research aims to test and further specify what a *suitable zinch-rich paint* should be and what pretreatment methods that can be used with different type of paints. Further, the standard does not deal with old or consumed HDG-coatings. For refurbishing old HDG-steel, coatings that do not offer cathodic protection can also be a good alternative.

5.2 ISO 14713- series

This standard series include two standards covering recommendations for steel to be galvanized:

- *Zinc coatings – Guidelines and recommendations for the protection against corrosion of iron and steel in structures – Part 1: General principles of design and corrosion resistance (ISO 14713-1:2017)*
- *Zinc coatings – Guidelines and recommendations for the protection against corrosion of iron and steel in structures – Part 2: Hot dip galvanizing (ISO 14713-2:2019)*

It is important to note that any special requirements regarding pretreatment and steel composition must be specified in addition to the general ISO 1461 standard for HDG-coatings. Hot dip galvanizing requires a steel design that is compatible with the hot dipping process. Some of the design requirements presented in the ISO 14713 includes notching and draining specifications that must be followed to ensure a safe dipping process. Others requirements such as content of alloying elements of the steel is necessary to control the thickness of the resulting HDG-coating. Usually there is no need to blast clean steel that shall be hot dip galvanized but blasting is recommended for annealed steel and other heat treatments such as thermally cut edges. The reactivity of the steel is affected by the heat treatments and it is therefore a good idea to require a pretreatment by grinding of thermally cut edges as per the preparation grades P2 or P3 according to ISO 8501-3. In contrast to painted coatings HDG does not normally require rounded edges to get adequate coverage on edges. However, some clients order HDG-steel with rounded edges to minimize damage during transport and assembly of the steel. A pretreatment of P3 for edges is also important if the HDG-steel is to be painted after galvanization to afford a duplex system.

5.3 Standards for painting power transmission towers

NACE International together with Institute of Electrical and Electronics Engineers (IEEE) have written three standards that deal with inspection and maintenance of power transmission utilities:

- *Atmospheric (Above grade) Corrosion Control of Existing Electric Transmission, Distribution and Substation Structures by Coating Systems*
- *Below-Grade Corrosion Control of Transmission, Distribution, and Substation Structures by Coating Repair Systems*

- *Below-Grade Inspection and Assessment of Corrosion on Steel Transmission, Distribution, and Substation Structures*

These documents address the specific problem of maintaining both HDG steel and previously painted steel on high voltage transmission utilities. However much of the content in the standards can be useful for other types of structures as well. Some of the statements in the Atmospheric (Above Grade) standard are as follows:

> *Determining the optimal timing for refurbishments is one of the most critical factors when planning a maintenance program for power utilities. There are no easy way of calculating a best plan for refurbishments.*

Instead the standard suggest to thoroughly inspect the assets and via reoccurring inspections classify each structure into different categories of coating degradation. Such degradation can then be used to monitor the corrosion and to plan for refurbishments. In order to plan a successful maintenance it is also very important to choose the right coating. Different coatings require different pretreatment and also have different limitations when it comes to.

6 Inspecting HDG steel

Inspecting HDG-steel for corrosion damage is somewhat different from inspecting steel coated with non-metallic protective coatings. Painted steel that has started to rust is relatively easy to spot by examining the steel visually for damage. Corrosion hot-spots, rust spots, flaking, cracking or blistering in an organic coating is usually assessed visually according to the ISO 4628 series. Coating defects of this type will generally constitute weak points in the coating that sooner or later will be accompanied with rusting of the base material. Particularly the rust grade standard EN ISO 4628-3 is commonly used to assess degradation and need for recoating of coated steel.

6.1 Inspecting HDG with alloy corrosion

When it comes to HDG steel, the method described in EN ISO 4628 is not ideal. A HDG coating consists of several distinct layers of steel/zinc alloys, typically a HDG coating will consist of up to four layers with varying amount of steel content. See ***Figure 8***. When the outer zinc layer of a HDG coating has been consumed, the degradation of the coating will continue with consumption of steel/ zinc alloys. The steel alloys give rise to brownish corrosion products that may appear as rust. This type of corrosion is often called alloy corrosion of HDG. Because the steel/zinc alloys also have a good protective effect, any corrosion assessment of HDG-steel must include coating thickness measurements of the coating. Further, to correctly perform thickness measurements the coating must be treated by scraping or steel wire brushing to remove any corrosion products that may have built up on top of the HDG coating. See examples of HDG steel measurements in ***Figure 9*** to ***Figure 11***. The figures show that a brown/ rusty looking HDG steel may still contain enough zinc for decades of adequate corrosion protection. The figures also show that corrosion products present on the HDG coating will influence the measurement if they are not properly removed before the measurement.

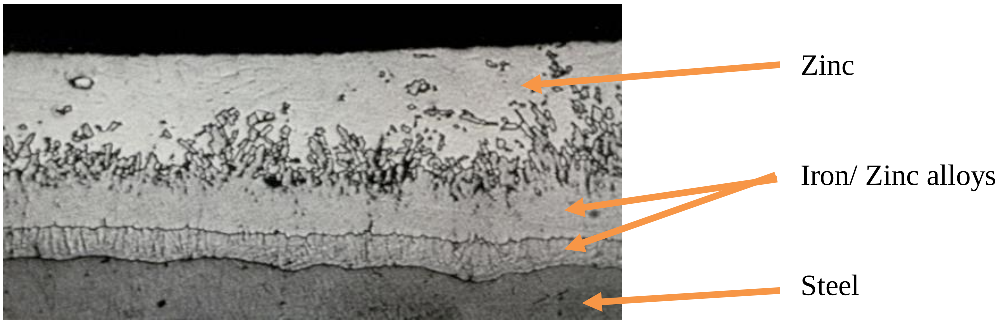

Figure 8*. Micrograph of a HDG coating with distinct phases, courtesy of Nordic Galvanizers. The iron rich zinc phases gives rise to corrosion products that resemble red rust*

Figure 9. *Coating thickness measurement on a lamppost, to the left, measurement as found indicate a thickness of 86 µm. To the right: measurement after scraping gently with a knife held at 90 degree angle, indicate a coating thickness of 0 µm, (the -0.6 µm reading is within the error margin of the instrument).*

Figure 10. *Coating thickness measurements of HDG steel of a 48 year old power pylon placed nearby the E4 freeway in the Stockholm area. To the left: leg furthest away from the traffic, To the right: leg closest to the traffic. Loose corrosion products were scraped using a steel wire brush to produce the blackish surface, further treatment with a 100 grit paper produced a surface with metallic sheen equivalent to a St 3 surface according to ISO 8501-1. Different treatments produce significantly different thickness measurements. It is also noteworthy that the thickness was almost double on the leg furthest to the freeway, in other words, film thickness can be very local. Varying film thickness can be differences from the HDG process or local variations in corrosivity.*

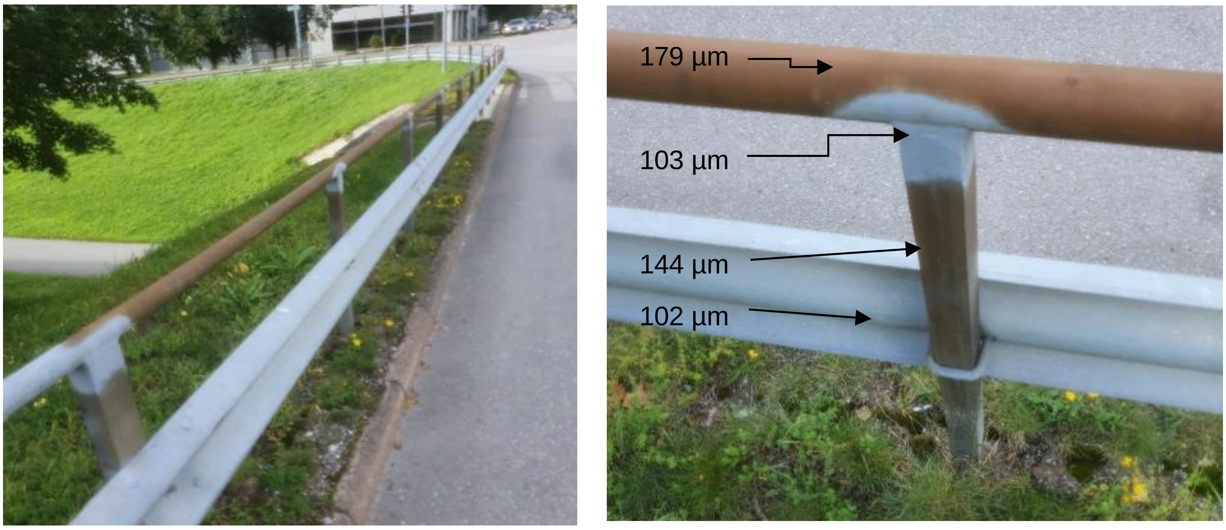

Figure 11. *Coating thickness measurements of HDG and TSZ of a road fence with unknown service time. Note the alloy corrosion on the fence poles and the rail. Despite the rusty look of the alloy corrosion the coating thickness of the poles and the rail is thicker than the coating on the W-profile (102 µm) and the TSZ (103 µm). All measurements were taken after wire brushing a small area of the coating.*

6.2 Inspecting HDG steel cast in concrete

When inspecting rusty HDG steel cast into concrete, it is always a good idea to perform contact measurement between the HDG steel member and the cast-in rebars. If there is an electrical contact between the reinforcement and the HDG, it is seldom meaningful to try to repair corrosion damage in the HDG coating. In such cases it is necessary to break the electrical contact before attempting any repairs. The only other options is to protect the HDG steel with cathodic protection with impressed current or to redesign the anchoring of the HDG steel member. In this context, it is worth mentioning that some installations require electrical neutrality and contact between the rebars and all protruding steel members. Such installations are for examples bridges over railways. The reason is to avoid electrification of steel members as a result of powerline failure. In these instances electrical safety is prioritized over the risk for corrosion damage. If the requirement is such that the rebars must be in electrical contact with any protruding steel members, a good solution is to use stainless steel anchoring points. Stainless steel has a corrosion potential which is similar to carbon steel cast in concrete. The contact between the stainless steel and the HDG steel can be located vertically higher up to effectively reduce the wet time of the anodic zinc coating.

6.2.1 Contact measurements for HDG cast in concrete

If a repair of HDG steel cast into concrete is planned, the corrosion damage should always be inspected to assess if the corrosion is a uniform general corrosion or if the damage could have been caused by galvanic corrosion due to contact with the cast-in reinforcements. To check whether there is a risk of galvanic corrosion, the reinforcing steel needs to be exposed and the electrical resistance between the HDG steel and the reinforcement must be measured. In the case of electrical contact, a resistance of less than 1 ohm is typically measured. If the resistance between HDG steel and the reinforcement is greater than 100 ohms, there is no contact. If the resistance is between 1 and 100 ohms, the particular installation should be investigated further by measuring the corrosion potential of the HDG steel. In such cases, the corrosion potential of the HDG steel should be measured while applying a direct current between the reinforcement and the HDG steel. If the corrosion potential of the HDG is the same with and without current, this is proof that the HDG steel is in electrical contact with the rebars. If a sharp change in the corrosion potential of the HDG steel occurs while applying the current, this is proof that there is no electrical contact between the HDG steel and steel reinforcement.

6.2.2 Contact localization measurements

If it has been established that electrical contact exists between HDG steel and steel reinforcement, a location measurement may be made to find where the electrical contact point is located. Below is an example of a localization measurement on a HDG steel railing on a bridge.

An alternating current is applied between the hot-dip galvanized railing and the steel reinforcement. By using an amperemeter, the path of the current in the railing can be followed. The pathway of the current can then be used to determine which of the railing posts that are in contact with the rebars. When unintentional contact points have been located the reinforcing steel can be exposed and the contact broken. The galvanic corrosion will then be eliminated and the partially cast-in HDG steel can be repaired with one of the methods suggested in this document.

6.3 Case study - HDG steel structure inspection in Kättbo, Sweden

This case study is an inspection of old HDG steel structures that has been used as a platform for a transformer/ switchgear station in Kättbo, Sweden. The asset is owned by Swedish powergrids and managed by Vattenfall. The structures were built in the late 1950's and the steel was about 60 years old at the time of the inspection. The old power transmission equipment needed to be replaced to meet the current transmission needs. The aim with the inspection was to clarify if the old platform structure could be reused, or if the new equipment should be installed on a new HDG steel supporting structure. More specifically, the asset owners wanted to ascertain that the old structure would manage at least 25 more years of service with regards to risk for corrosion damage. The assignment was given to Charlotte Persson, AFRY and the inspection of the existing steel was conducted by Björn Stam, St Control. The steel inspection was performed on the 16th of December 2020. The inspection was carried out from ground level and from one of the platforms, see pictures below for details of some of the problems found during the inspection.

Figure 12. *Overview of the transformer platform that was inspected. Generally no signs of critical corrosion damage were found. The main I-beams have developed alloy corrosion.*

Figure 13. *To the left: Main I-beam with alloy corrosion and corrosion hot-spots in damages of the HDG coating. The hot-spots may be the result of corrosion in a crevice where corrosion rates may be higher due to prolonged wet time. Top right: A HDG I-beam with alloy corrosion and an I-beam with discoloration from extraneous rust. Lower right: HDG coating thickness measurement. The HDG coating thickness was about 200 µm after scraping the superficial corrosion products.*

Figure 14*. Spot-wise delamination and areas with low zinc thickness. This damage has probably come from the HDG process.*

Figure 15. *Damage in the HDG coating down to the steel substrate. The damage was located in a position that makes the cause likely to be flaking due to mechanical damage during transportation or structure assembly.*

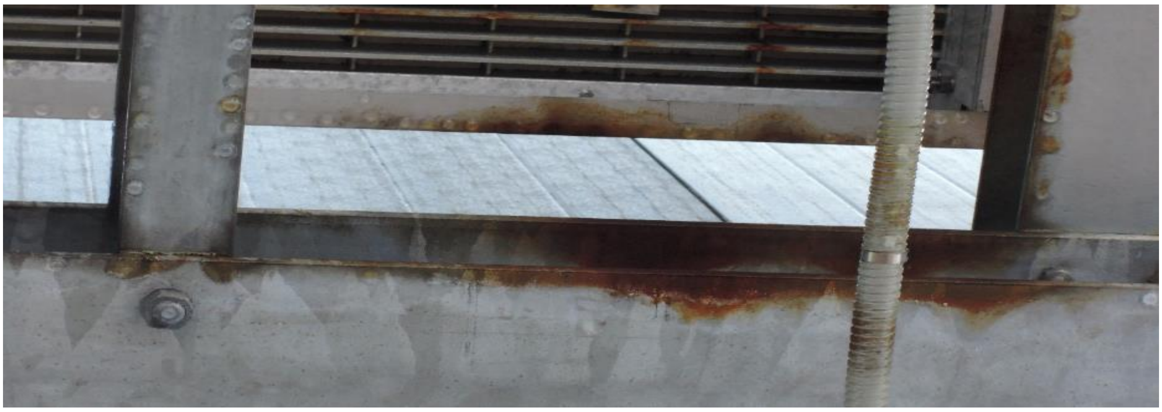

Figure 16. *Discoloration from extraneous rust.*

Figure 17*. Sharp edges of HDG steel. If the HDG has adequate adhesion to the steel, sharp edges often not a problem with regards to corrosion. Rounded edges may however be motivated if the steel shall be coated with paint products to obtain a duplex coating, or if wear or impacts is anticipated during shipping, handling or service of the steel members. Thermally cut edges may produce a HDG coating with insufficient coating thickness and adhesion to the steel.*

6.3.1 Conclusions and suggested actions

The general impression of the steel appearance is that the steel is in very good condition. The HDG does not show significant corrosion damage such as adhesion problems, flakes, layering, etc. Some parts of the horizontal beams showed a discoloration indicative of alloy corrosion on the upwards facing surfaces. The zinc with alloy corrosion was inspected by scraping of corrosion products and measuring the coating thickness according to EN ISO 2808. The thickness of the coating after scraping was found to be around 200 µm. The total area of coating damage exposing the underlying steel was small. Furthermore, most of the damage was located in non-critical areas. The conclusion is that the steel structure can be reused with minimal or no further treatment in order to prolong the expected life of the steel structure. One of the I-beams showed hotspots of corrosion on the flange see ***Figure 13***. This damage should be addressed in order to secure an expected life of more than 25 years.

7 Repairing HDG coatings

Maintenance of HDG steel should be divided into two subcategories, repairs and refurbishment. In this study we will use the term repairs for any treatment of a small damage to the coating of a HDG steel structure. It could be mending mechanical damage due to shipping, correcting surfaces affected by welding or treatment of corrosion hot spots on a relatively small area. A repair should always be considered on mechanical damage on newly built HDG structures. If the damage is located at a critical point of the structural design it may be advisable to exchange the damaged part instead of attempting a repair. A repair might be beneficial where the complete zinc layer has been corroded or damaged exposing the underlying steel substrate. In many installations, transport and assembly damage are located at edges of profiles, bolt ends or on the edge of an H-bar flange. In such instances a repair is often sufficient to give an adequate protection for the steel. Depending on the corrosivity a repair of such damage might be performed with minimal pretreatment using portable power hand tools. In low corrosivity small damages on non-critical places can often be left without repair.

A refurbishment of a HDG steel structure would in contrast to repairs treat a larger part of the structure, Typical examples are recoating an old structure with depleted zinc coating or correcting new steel members with a HDG coating with too low DFT. Refurbishments are often done in the field on existing structures and requires more careful planning. Any in-field refurbishment must address the need of confinement during pretreatment or access of the steel members to be coated, drying/ curing times for the products used and climatic restrictions. For in-field refurbishments it is also important to consider the downtime of the asset. Timing of the treatment is also important, normally it would be desirable to perform a refurbishment when as much of the remaining zinc on the existing HDG steel is consumed, yet if the refurbishment is postponed too long that will adversely affect the cost due to a much more comprehensive pretreatment procedure that is usually needed for a structure which has begun to show corrosion damage on the steel substrate.

HDG-steel is used for many different applications, ranging from road fencing, railing, railing posts, street light lamp posts, power transmission towers and walkways in industrial production plants. It is therefore not possible to find one specific product that covers a general best practice for repairing or refurbishing HDG steel structures. Rather one must look at different methods and products to cover different requirements for the range of environments that HDG-steel might be used in. Therefore, this study has focused on a few different products and pretreatment methods with an aim of creating a toolbox of different protocols that might be useful in different applications. All methods studied have different advantages including investment costs, environmental footprint and effectiveness. A common feature that we have focused on is ease of use. Of primary importance to increase ease of use is to limit the required work steps as much as possible. A repair method comprised of pretreatment and a multilayer coating system is likely to be too cumbersome. In this study we have therefore concentrated our efforts to investigating single layered coatings also known as “stand-alone coating systems”.

8 Pretreatment methods studied

During this work, a few different surface pretreatment methods were investigated. The surface preparation prior to coating work is one of the most important factors for achieving a good corrosion protection. However, pretreatment is often laborious, costly and one of the big contributors to environmental impact and diffuse emissions of hazardous materials. It is therefore important to choose pretreatment method carefully. The pretreatment methods that were used in the corrosion testing of this study were chosen based on some experimental investigations. The studied pretreatment methods include, abrasive blasting, slurry blasting, vacuum blasting, laser cleaning and two versions of hand/ powertool cleaning. Some characteristics of the different methods have been included in the following sections.

8.1 Blasting and Vacuum blasting

Blasting under vacuum is an interesting technology that could reduce the environmental impact and cost of repairing corrosion protective coatings by providing fast and convenient method to spot repair damage in protective coatings and HDG-steel. Vacuum blasting is blasting equipment that allows simultaneous blasting and vacuum cleaning without the need to build confinements. Nozzles with different designs to suit goods of different geometries such as pipes, I-beams, corners, flat surfaces, etc are available on the market. The primary advantage of this method is that it can lead to a reduced need for confinement when blasting. One problems with vacuum blasting is that it is more time consuming than normal blasting and it might therefore be considered mainly for spot repairs. [39] [40]

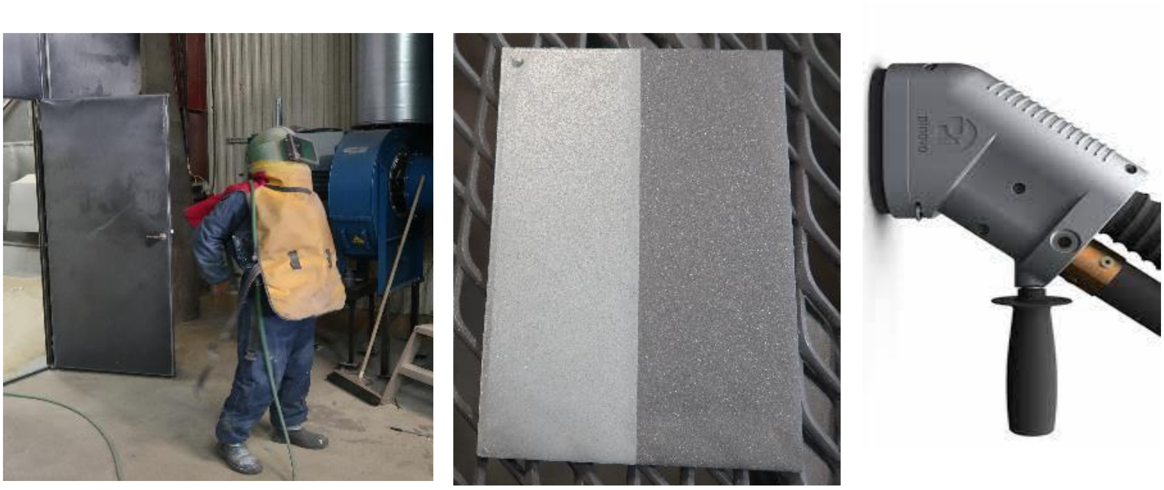

Figure 18. *To the left: Blasting in controlled environment is often performed using metallic abrasives. For coating HDG steel it is best to keep as much as possible of the intact zinc and use lower pressures and perform a light blast using inorganic blasting media. In the middle: samples used in this study were blasted to a fine profile with OK grit 55. To the right: vacuum blasting nozzle as depicted at www.pinovo.com. This type of nozzle is suitable for small repairs where dust should be minimized.*

8.2 Slurry blasting

Slurry blasting is a method where water is added to the abrasives into the jet in the nozzle of the blasting hose. The water added has two effects: first and foremost the work environment is less hazardous as the water tends to encapsulate the dust generated when the abrasives impact the substrate; secondly, the amount of water can be regulated to afford a washing of the substrate at the same time as a surface profile is created. During this project a short practical study of the slurry blasting technique was performed at Anti-corrosion AB in Sundbyberg, Stockholm, see ***Figure 19*** and ***Figure 20***. Bresle measurements according to ISO 8502-6 and ISO 8502-9 showed a salt content of 25 mg/ m2 after slurry blasting of a piece of road W-profile fencing. Because the water is introduced at a late stage, it is possible to perform slurry blasting with a relatively low pressure which makes it suitable for pretreating HDG-steel. One problem with all types of wet blasting is the visibility of the workpiece. Vapor that forms when the water impacts the substrate makes it harder to adjust to the optimal blasting time.

Figure 19. *To the left: slurry blasting equipment. To the right: HDG steel structure blasted with slurry blasting equipment, with slurry blasting as with all other blasting techniques it is important to adjust the impact angle and blasting pressure to achieve optimal cleaning. When blasting HDG this is even more important because HDG layers have a tendency to fall off if blasted too hard.*

Figure 20. *Road fencing that has been partly blasted with slurry blasting. One of the advantages with slurry blasting it that it is relatively easy to wash the surface before blasting, as well as during blasting. Bresle measurements after slurry blasting showed a low salt content on the surface, 25 mg/ m^2.*

8.3 Power tool cleaning

Abrasive blasting usually gives the best results for any type of zinc rich coating, but sometimes it is necessary to use other types of pretreatment. Local damages and corrosion hot spots might be too time consuming to pre-treat using abrasive blasting, especially on a larger structures. The structure can also be placed in environments where blasting is impossible or prohibited. Hand tool cleaning tends to give less than optimal pretreatment, at least for zinc-rich coatings, and one alternative pretreatment investigated in this study is power tool cleaning. Investigated power tool cleaning methods were low rpm disc grinding and a rotary impact tool, also known as Bristle blaster, see figure 20.

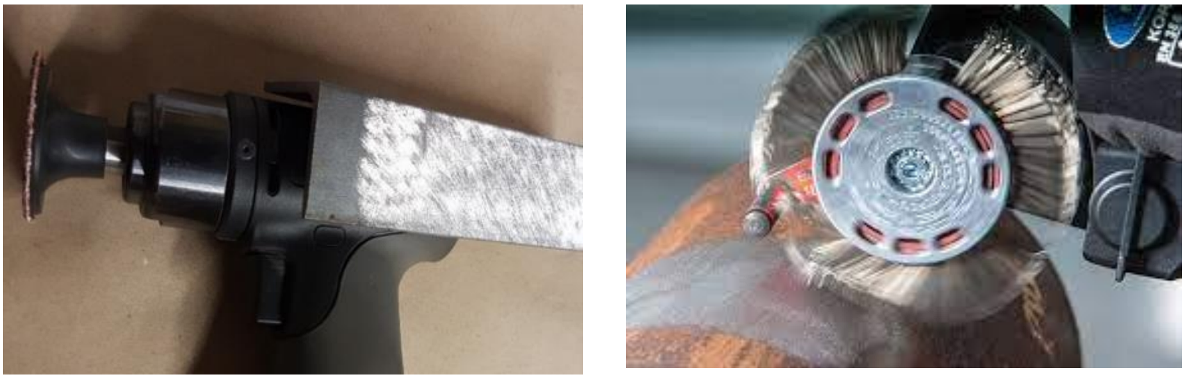

Figure 21. *Pretreatment methods evaluated for spot repairs, to the left hashed grinding with a small disc (DIA 50 mm, 36 grit paper). To the right: bristle baster in action as depicted at www.montipower.com*

The bristle blaster was evaluated on different HDG steel. It was apparent that it can be a very effective tool for creating a surface profile on HDG-steel. However the effectiveness of the bristle blaster appears to depend on the type of HDG. On the sample specimens that were chosen for the outdoor exposure in this study, the bristle blaster was not optimal and resulted in a buffing of the substrates rather than a profiling. The buffing/ profiling result is probably dependent on the thickness of the HDG coating and the hardness of the steel/ zinc alloy of the substrate. The outer zinc layer on a HDG steel is very soft, but the steel/ zinc alloys are much harder**,** and can in fact be harder than the steel itself.

Pretreatment by grinding was performed with a small 36 grit disc grinder with variable speed. High speeds can be good for bevelling edges and surfaces to be coated was ground with low rpms. The low grinding speed and grinding in hashed patterns is good to give pattern which can serve as anchoring points to assist adhesion to protective coatings, see figure 21. Pretreament by grinding works well for both steel and different kinds of steel/ zinc alloys.

Figure 22. *Results after spot repair pretreatment. Hashed grinding to the left of the black indication, bristle blaster to the right.*

8.4 Laser cleaning

A relatively new method to effectively remove old paint and rust before painting is the use of a pulsed laser, a method called laser ablation. The mechanism of the method is that a laser is pulsed to the surface wherein a microscopic plasma is generated which sublimates the solid impurities. The plasma also creates a pressure wave which helps to release larger particles from the surface. The technology is available in many different designs. These include a hand-held gun that also has an integrated vacuum assembly to capture liberated gas and loose particles. The extractor is connected to the same nozzle as the laser beam and the flow of air is then purified in a multistage filter box, see Figure 22. Advantages of this method are that it removes contaminants like oil, grease, rust and chlorides at the same time. The method requires no abrasives, water or other supplies. Potentially, it is a very effective method to use instead of sweep blasting. [41] Laser cleaning might be considered for spot repairs of complex structures in-field. It can also be advantageous for refurbishment or repairs when blasting is not possible or permitted. Pretreatment using laser cleaning may, or may not produce a surface profile of the underlying substrate. On the L-Profile samples used for corrosion testing in this study, the average surface roughness of the laser cleaned sample specimens were deemed to be surprisingly good.

Figure 23. *Handheld laser 1000W as depicted at www.agaria.se. Laser nozzle in the foreground and aggregate in the background.*

An issue of interest is how the method affects the work environment. Noise levels are much lower than normal blasting. The particle size distribution of the particles released from the plasma, the effectivity of the particle collector and what fraction of the vaporized material that can pass the filtering are all parameters that will affect the work environment. Agaria is the Nordic agent for Clean Laser ™ with offices and a small test facility in Åkersberga. As part of this project a visit to Agaria was made. During the visit, a number of tests with laser cleaning on galvanized steel were performed. The test specimens were a galvanized pole exposed in soil (unknown time), a hot dip galvanized rebar that had been exposed embedded in concrete (unknown time) and a zinc panel exposed at RISE's field exposure site in Vanadis, Stockholm, for about 10 years. Part of the exposed zinc panel was smeared with oil the day before the experiment. The laser equipment available during the visit was a 100 W laser. Which was enough to produce satisfactory results on the HDG steel exposed to atmosphere but not for the samples exposed in concrete and soil. photos of the HDG specimen in ***Figure 24***. After the laser cleaning, the surface of the zinc was investigated using ATR-IR, see ***Figure 25***.

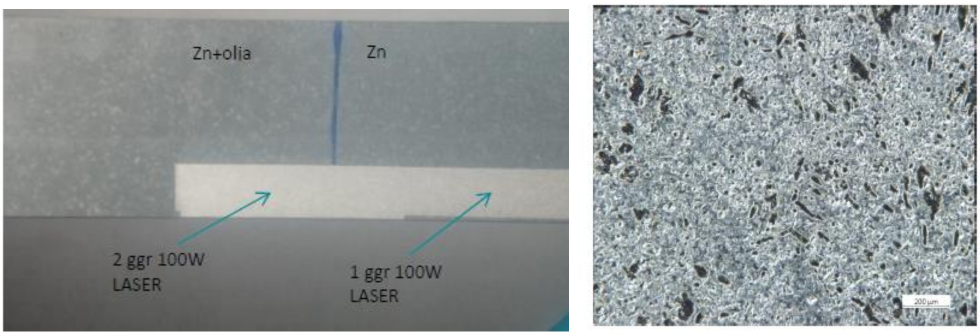

Figure 24*. To the left: HDG steel before and after pretreatment with laser. To the right a micrograph of the HDG surface*

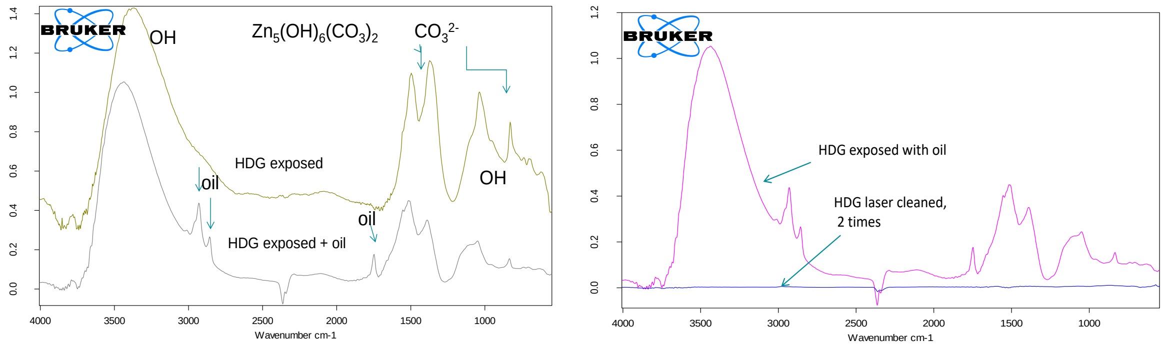

***Figure 25**. To the left: shows a superposition of two IR spectra recorded from the exposed zinc plate. One of the spectra shows zinc corrosion products, and the second spectra shows the part of the zinc sheet that was treated with oil. To the right: a comparison of the spectra of the oil treated zinc plate (purple) and a surface that has been treated with two sweeps with a 100 W laser (blue). The right hand spectra clearly show that both the corrosion products and oil was quantitatively removed.*

9 Coating products investigated in this study

In the below sections a short summary of each coating or coating type included in the exposure part has been compiled. The information is taken from product data sheets and discussions with the respective paint manufacturers.

9.1 Zinga

Zinga is a stand-alone zinc-rich coating with high zinc content of 97% by weight in the dry film. The zinc pigment in the product is produced by an atomization process, which provides high purity and tailored morphology of the zinc particles. Zinga is a physically drying coating with unlimited pot life and very short drying times, 1-4h depending on the ventilation and temperature. Application is possible in a wide temperature range, -10 °C to 45 °C. It is also relatively insensitive to moisture during curing, it is possible to apply in relative humidity (RH) of up to 90 %. The product is intended to be used on clean abrasive blast cleaned surfaces. The product is relatively high in VOC but with a specified nominal dry film thickness of 120-180 µm the total amount of VOC per square meter can be lower than traditional C5 systems with specified nominal dry film thickness of 320 µm. The product has been developed in Belgium with an aim of producing a coating that is specifically tailored for maintenance of HDG-coatings. Maintaining an aged Zinga coating can be done simply by a high-pressure wash followed by application of a new coating layer. The new layer will then (in part) dissolve the old paint and reload the coating with new zinc. This results in a coating that can be comparatively easy to maintain, especially on assets such as ships, oil platforms and in industry where a frequent ad hoc maintenance procedure can be utilized.

9.2 Aqua Zinga - waterborne zinc silicate

Aquazinga is a two component 100% water-based zinc silicate with 94% zinc by weight in the dry layer. Like Zinga, the zinc particles are made by an atomization process, which provides a tailored morphology of the zinc particles. The VOC content of Aquazinga is 0 g/l, which lower environmental impact and reduces health hazards compared to solvent based formulations. It can be used as a stand-alone system at 75- 90 µm film thickness or used as primer at 50-60 µm in duplex or triplex systems. The quick drying time makes it possible to overcoat Aquazinga 1 to 6 hours after touch dry. Aquazinga is suitable for either atmospheric exposure or immersion into fresh or sea water. It has a high resistance towards solvents. Once applied, it can withstand continued temperatures up to 450°C and peak temperatures up to 600°C.

9.3 ZingAlu

ZingAlu is a newly developed product which is very similar to Zinga. It is produced by Zinga Metal but in contrast to Zinga, the ZingAlu is pigmented with both zinc and aluminium. Since the ZingAlu is a new product, not so much is known about the possible benefits from this system.

9.4 Zinc Ethyl Silicate

Zinc ethyl silicate is available from most paint manufacturers and in this study it has been exemplified by Temasil-90 provided by Tikkurila, and by Carbozinc 11, provided by Carboline. This type of paint is cured by transesterification of alkoxy silicates. The silyl alkoxides react with moisture from the atmosphere to form polymeric zinc silicate. In the process, alcohol is liberated, and the final paint film is in theory completely inorganic. The curing requires high humidity during application and the application is a little more tricky compared with zinc rich epoxy primers as outdoor use relies on a comparatively small window in the relative humidity, e.g. product data sheets for the zinc ethyl silicates tested in this study states; 50-90 % RH for Temasil 90, and 30-95 % RH for Carbozinc 11 for a successful application. According to most product data sheets, this type of coating requires clean blasted substrates to adhere well in a coating system. This type of coating has previously been used extensively in the offshore and shipping industry. Combined with a chlorinated rubber topcoat it has also been used as part of a bridge system in the Swedish infrastructure. Using zinc ethyl silicate as a stand-alone system would eliminate the troubles of a premature overcoat that can be a problem when zinc ethyl silicates are used in multi-layered coating systems. It is therefore interesting to evaluate zinc ethyl silicates as a single coat system. This could provide a cost-effective repair or refurbish coating for HDG steel. The use of ethyl zinc silicate as a stand-alone system could also reduce the amount of VOC and limit the use of sensitizing chemicals such as epoxy or isocyanates.

9.5 Fontezinc HR - Waterborne High Ratio Zinc Silicate

Fontezinc HR is a waterborne zinc rich coating based on high ratio potassium silicate. The coating has a high pH and is cured primarily by zinc ions from the zinc dust pigmentation. The coating normally requires blasted surfaces but also performs well on ground steel or zinc provided that the coating is applied with a brush. Being waterborne, it has a comparatively large window of acceptable relative humidity compared with zinc ethyl silicates. It is possible to use if the RH is higher than 20%. A too high RH will increase the drying time but will not affect the curing or the coating properties. The coating is very interesting for maintenance of HDG steel for the following reasons: the coating has 6 g/L VOC content; it contains no sensitizing chemicals such as epoxy or isocyanates.. The zinc in waterborne zinc silicates is passivated by the silicate binder and the pigmentation corrosion is therefore relatively slow. Fontezinc HR may also be a good alternative to HDG coatings in severely corrosive environments such as marine or offshore applications. A drawback of the coating is that it is waterborne, and as such, it requires more careful pretreatment, all surfaces must be completely free from oil and dirt for the coating to be able to wet the substrate.

9.6 Induraguard 9200

Induraguard 9200 is a high-solids, high-build, single-component, self-priming one-coat solution for weathered galvanized and previously painted structures. The binder in the Induraguard 9200 is a modified linseed oil that contains zinc dust, micaceous iron oxide and ceramic pigments to provide a sacrificial barrier protection. The coating is designed to be used on marginally prepared surfaces by hand tool cleaning using wire brush, scraper and other similar suitable hand tools according to SSPC-SP2. Application is mainly done by brush, roller or paint mitt. The combination of anti-corrosive and barrier pigments added in the modified linseed oil sums up to a total volume solids of 92% (± 2) and therefore resulting in a low VOC content This type of coating specially designed for maintenance has been used since the late 1950s in the United States for refurbishment and protection of electric transmission towers and other similar structures when the asset owner seeks a solution that do not require abrasive blasting. Linseed oil and alkyd type paints cure by oxidation when exposed to air and are usually specified with 2-3 coats each consisting of 50-60 microns DFT and requires sufficient time to allow proper curing before applying subsequent coats. In comparison the Induraguard 9200 is often specified with one single coat at 250 micron DFT and therefore resulting in a slow drying coating compared to many others. As with all coatings that cure by oxidation, the paint film cures from the top and downward to the substrate. The Induraguard 9200 is no exception and according to the technical data sheet, a dry enough surface for light touch is achieved within 12-24 hours at 25 ^{o}C and it is fully cured in 30-60 days. These slow curing properties are intentional and aids the coating to fully penetrate and wet out small voids in a less than optimal prepared surface. In the NACE SP0315-2015/IEEE 1835-2014 standard, this type of coating is listed by the name of *Long Oil Zinc.*

9.7 Biltema canned zinc spray

Zinc spray suitable as rust protection on iron/steel surfaces that are not normally painted, e.g. exhaust pipes, welding joints, surfaces on the inside of the engine compartment and bodywork. Zinc content 90% in dry film. The cold galvanization has good coverage and dries quickly, the surface is manageable after 30 minutes. The surface can withstand temperatures of up to approx. +200 °C. [14]

9.8 Bridge system

In this study, one reference bridge system in accordance with the requirements in AMA-anläggning has been tested and evaluated along with the alternative systems. The bridge system has been included because it is a widely used coating system with generally known performance. It may therefore serve as a benchmark when comparing results from the alternative systems investigated. The reference system tested is composed of a zinc rich epoxy primer (90% Zn), a MIO-pigmented epoxy midcoat and a polyurethane topcoat.

10 Accelerated corrosion testing and electrochemical evaluations

Products proposed for HDG-maintenance in this project are also interesting products for protecting various steel structures. In a separate project financed by the Swedish Road Administration and RISE, all product types considered for HDG maintenance have been investigated as corrosion protection for steel substrates by accelerated corrosion testing and simple electrochemical analysis. [15] A summary of that project has been included here. Section 10.1 includes a summary of the results from accelerated corrosion tests, section 10.2 includes results from electrochemical measurements and section 10.3 includes a discussion on the most important findings from the study.

10.1 Accelerated corrosion testing

Accelerated corrosion tests are used methodically to develop protective coatings. Usually they are used to screen coatings and find leads to formulations that have a high probability of giving good corrosion protection in real life installations. Many accelerated corrosion tests have also become necessary pre-qualification standards that protective coatings must pass in order to be viable for marketing. However, accelerated corrosion tests can stress coatings in an unnatural way and may give misleading results. [16] [17] [18] It is well known that zinc coatings require periods of dry conditions to perform at their best. Consequently, salt spray or similar tests with high humidity often gives poor correlation to outdoor atmospheric corrosion tests on zinc-rich coatings. Therefore, accelerated corrosion testing should always be interpreted with care, and if possible be accompanied by field exposures in environments similar to the service environment, and reference objects if possible. The best results in the corrosion testing was observed with a stand-alone zinc-rich epoxy. The zinc epoxy was slightly better than the waterborne zinc silicate, followed by the zinc ethyl silicate. The topcoated three layered coating systems with zinc rich primers showed slightly worse rust creep at the scribe compared to the stand alone zincs. The Zinga and ZingAlu systems did not perform well in the VDA test. However, Zinga performed good in the ISO 12944-9 test. The VDA protocol has an overall longer wet time and a higher mean temperature (above 40 °C) during exposure to chlorides. The ISO 12944-9 test includes periods of dry air during the UV part of the condense/ UV cycle. As a result of this, much more insoluble zinc corrosion products could be seen on the samples exposed in the ISO

12944-9 test. The combined effect of lower temperature and longer dry periods is probably one reason why the Zinga systems performed better in the ISO 12944-9 test.

10.2 Results from electrochemical measurements

Measuring the open circuit potential (OCP) is a method of getting a first idea of the reactivity of a galvanically active coating system. OCP often varies with time and a shifting OCP is an early indicator that surface properties are changing. Changes in OCP can occur as a result of corrosion, degradation of a protective layer, water ingress into a coating or depletion of zinc in a zinc pigmented coating. In the case of a zinc-rich coating on a scribed steel surface, the measured potential will be a mixed potential between that of pure zinc, (approx. -1000 mV and that of pure steel, (approx. -600 mV) versus a Ag/ AgCl reference electrode in a 3% brine solution. A mixed potential indicates that the zinc and steel have electrical contact and that the zinc is polarising the steel, ie. protecting it. Another way of viewing it is that a measured potential close to -1000 mV is an indication of corrosion of zinc, whereas a potential close to -600 mV is an indication of corrosion on steel. If the potential is somewhere between -1000 mV and -600 mV that indicates that both steel and zinc are corroding. The OCP can therefore be used as a tool to measure if the zinc coatings are able to give a galvanic protection to the steel. Generally, a mixed potential lower than -850 mV indicates a steel/ coating system where the steel is galvanically protected. To investigate the galvanic activity of the tested coatings all coatings have been investigated by measuring the OCP variation over time. From the measurements it is clear that different coatings have different galvanic activity, Zinga and ZingAlu was the most active (E < -1,0 V), Zinc ethyl silicate is less active than Zinga (E ~ 0,95 V) but more active than zinc epoxy (E ~ 0,88 V), water borne zinc silicate showed initial passive potentials (E ~ -0,3 to -0,5 V). First after about 20 hours the potential indicates galvanic protection (E ~ -0,80 V). All coatings except ZingAlu provided galvanic protection to the steel for more than 400 hours. To further investigate the galvanic action of the stand-alone zinc systems, OCP measurements on scribed samples were performed. The results showed that most stand-alone zinc rich coatings can provide a galvanic protection to the scribe. ZingAlu appears to be relatively quickly depleted as the corrosion potential rises comparatively fast. Water borne zinc silicate again showed slow initiation of the galvanic action and was able to protect the steel for a comparatively short period, indicating a poor galvanic protection. The three coat systems could only be studied on samples with a scribe. Three coating systems conforming to C5 07 of ISO 12944-5 were tested. Two of the systems were very similar and were able to protect the scribe galvanically for about ten hours. In comparison, a system formulated with electrically conducting additives/ binder was able to protect the scribe galvanically for about 75 hours. Interestingly both zinc rich coatings with 80 % zinc by mass, gave similar or better galvanic protection compared to the 90 % zinc reference system.

10.3 Discussion

The zinc pigmentation in zinc-rich coatings behave differently depending on the coating vehicle. In other words, the properties of the binder and/ or other additives can affect the electrochemical activity of the zinc pigment. Silicate binders can inhibit the anodic reaction on zinc which makes the coating less reactive. Depending on the ratio of zinc and binder, epoxy binders can insulate the zinc pigmentation and thereby limit the galvanic effect from the zinc pigmentation. Zinc coatings can also be formulated with additives that increase the activity of the zinc.

The OCP measurements performed in this study indicate that the formulations with highest galvanic activity was Zinga and ZingAlu. The least active zinc was found in water borne zinc silicate. The pigmentation in zinc-rich epoxy and zinc ethyl silicate were found to be intermediate. This order of activity could explain some of the results from the accelerated tests. Zinga and ZingAlu are pigmented well above CPVC with a very active zinc, consequently the coating gives a good cathodic protection. On the other hand, the pigmentation is relatively quickly depleted. A faster consumption of zinc is probably why the Zinga formulations did not perform well in the VDA test. The corrosion of the zinc pigmentation in the waterborne zinc silicate is inhibited by the silicate binder, as a result the zinc particles are not consumed as fast and the coating gives a comparatively poor galvanic protection but the coating is not depleted as fast. Interestingly, in this study, the stand-alone zinc-rich coatings with the lowest galvanic action gave the better results in the accelerated tests. There are several mechanisms by which zinc-rich coatings can protect steel, these include:

- Galvanic protection
- Barrier protection
- Passivation of the steel and zinc pigmentation
- pH control/ buffering at the steel/ coating interface

It is clear that the expression of these mechanisms can be tailored by choosing an appropriate binder, additives and degree of pigmentation. Depending on the type of exposure it is not always best to have an active zinc. Rather, the key to success appears to be a moderately active zinc pigmentation.

11 Field exposures

It is well known [19] [17] [16] [18] that accelerated corrosion testing can be misleading and often show low correlation with atmospheric corrosion in real applications. This effect has been found to be particularly pronounced for zinc and zinc-rich coatings. To be able to draw any conclusions about which coating system that can be accepted for maintenance of HDG steel, the results from the accelerated corrosion tests must be complemented with natural weathering. In addition, many coating specifiers request that protective coatings shall be tested and approved by outdoor exposure before they may be used. The Swedish Road Administration and the building sector in Sweden currently have a requirement that all protective coatings intended for atmospheric exposure shall be tested at a marine test station with a corrosivity of C4-C5 for four years. Therefore field exposures were used as part of this study to test the proposed coating systems described previously.

11.1 Exposure sites

In this study, three different exposure sites have been selected. Exposure station at Ryda, google coordinates 59.761308, 17.128214. The site can be described as a rural area, the corrosivity is measured annually and is usually C2 for carbon steel and C3 for zinc. Exposure station Bohus-Malmön, google coordinates: 58.325998, 11.316686, can be described as a marine environment, approx. 50m from seashore. The corrosivity is measured annually and is usually C5 for carbon steel and C3 for zinc. Exposure station Borås, highway 40, google coordinates 57.704325, 12.837009, can be described as road environment, the samples are located approximately one meter from the freeway, corrosivity not quantified during this exposure, but previous exposures have indicated a corrosivity of C4 for steel and C4 for zinc along highway 40.

Figure 26. Location of exposure sites used in this study

11.2 Sample preparations

Samples of two different sample geometries were chosen for the exposures. One is a simple flat plate with a freshly prepared HDG coating, called Flat Panel in this report. This sample geometry was included to be able to compare the different coating systems with an optimally prepared surface. The specimens can be used as a benchmark for the different products investigated. Flat panels were pretreated by abrasive blasting to bare steel on one side, the cleanliness achieved was Sa 3. The surface profile corresponded to medium grit according to ISO 8502-3. The other side of the panels were sweep blasted to create a profile but minimizing the zinc loss. The surface profile of the zinc corresponded to fine according to ISO 8503-2. The abrasive used was non-metallic OK grit 55. After pretreatment the panels were coated with the different coatings according to the instructions of the manufacturer. Before exposure, the panels were edge protected by dip-coating with an aluminum pigmented epoxy mastic.

The second sample geometry was an L-profile taken from decommissioned power transmission tower and included fasteners (nut and bolts). The samples are named L-Profile panels in this report. Considering coating systems for maintenance one must deal with the fact that maintenance work might not always allow a perfect pretreatment. It is therefore interesting to also compare the products on samples with less than perfect pretreatment.

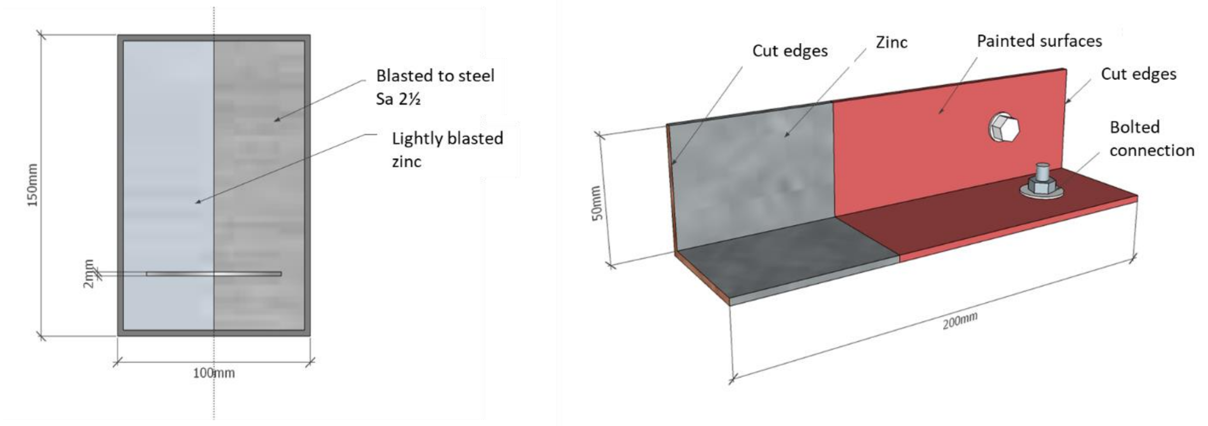

***Figure 27**. Sample plate design used in the outdoor corrosion testing. To the left: panels with new zinc coating as well as steel surface. To the right: L-profiles with with nuts and bolts coated with spot repair methodology*

L-Profile panels were machined from old L-profiles of a decommissioned power transmission tower. The machining was made with cutting fluid that might have affected the cleanliness of the substrates. After machining, all samples were washed with detergent in a Teijo C-2000 industrial washing machine. After washing, the panels were pretreated in one of the following ways:

- The panels were pretreated using laser cleaning technology with a 100W laser. The resulting surface profile was surprisingly good and could be compared to a fine grit profile according to ISO 8503-2. The observed profile may be a result of an incomplete removal of zinc corrosion products or it may be a result of shallow pitting profile formed in the substrate due to prolonged natural weathering.
- The panels were pretreated using a 5 cm wide disc grinder with a 30-36 grit paper. The speed was kept at a low rpm and the grinding was performed in hashed patterns to create a zig zag scoring of the sample surface. The grinding was performed to efficiently remove all corrosion products but leaving as much as possible of the underlying zinc coating intact.
- No additional pretreatment after washing

To accommodate correct application of the coatings the panels were prepared by approved applicators following the instructions of the manufacturer. The different panels were therefore prepared at different locations:

- Panels named N-P, B-D and F-I were pretreated and painted by IPM in a painting hall in Gävle.
- Panels named Q and R were pretreated and coated in a painting hall in Eskilstuna under supervision of Mettler Oerlikon.
- Panels namned S-U and J-L were pretreated and painted by Zinga in a painting hall in Falun.
- Panels named A, E and M were pretreated and painted by Tikkurila in a painting hall in Stockholm.

An overview of the samples and exposure sites is given in ***Table 3*** and ***Table 4*** below. ***Figures 28-30*** show the samples at the start of the exposures at the respective test sites.

11.3 Test matrix

Table 3. *Summary of the corrosion testing programme. Figures in the table represent number of samples of each sample type, pretreatment method and exposure station.*

Exposure Station	**Pretreatment**	**Sample type**		**Material (number of samples per repair methodology)**									
		Flat panels	L-Profile panels	Zinga	Aqua Zinga	Zingalu	fontezinc HR	EA spraying	Flame spraying	Zinc ethyl silicate	Zinc rich epoxy	Bridge system	Biltema 99% Zinc
Bohus-Malmön													
	Blasting	x		6	6	6	6	6/3	6/3	6	6	5	
	Laser		x	6			6			6	6	6	
	Powertool		x	6			6			6	6	6	6
Riksväg 40													
	Blasting	x		6	6	6	6	6	6	6	6	6	
	Laser		x	6			6			6	6	6	
	Powertool		x	6			6			6	6	6	6
Ryda													
	Blasting	x		3	3	3	3	3	3	3	3	3	3
	Laser		x	3			3			3	3	3	
	Powertool		x	3			3			3	3	3	3
Unexposed reference samples													
	Blasting	x		1	1	1	1	1	1	1	1	1	
	Laser		x	1			1			1	1	1	
	Powertool		x	1			1			1	1	1	1

***Table 4**. Summary of tested coating materials, pretreatments and mean coating thickness of tested samples*

Sample abbreviation	product name	Description	Sample type	Pretreatment	tot DFT	DFT Zn	DFT Coating	Number of coats
A	Fontezinc HR	Waterborne zinc silicate	L-profile	Laser cleaning	178	124	54	1
B	Temazinc 99	solvent borne zinc rich epoxy	L-profile	Laser cleaning	146	124	22	1
C	Temasil 90	Solvent borne zinc ethyl silicate	L-profile	Laser cleaning	147	125	22	1
D	Bridge system	solvent borne	L-profile	Laser cleaning	294	123	171	3
E	Fontezinc HR	Waterborne zinc silicate	L-profile	Grinding	128	72	56	1
F	Temazinc 99	solvent borne zinc rich epoxy	L-profile	Grinding	125	99	26	1
G	Temasil 90	solventborne l zinc ethysilicate	L-profile	Grinding	116	96	20	1
H	Biltema spray	solvent borne 1-c	L-profile	Grinding	124	101	23	1
I	Bridge system	solvent borne 1-c	L-profile	Grinding	306	96	210	3
J	Zinga	solvent borne 1-c	L-profile	Laser cleaning	184	125	59	1
K	Zinga	solvent borne 1-c	L-profile	Grinding	211	125	86	1
L	Induron	Solvent borne High solid	L-profile	Untreated	285	120	165	1
M	Fontezinc HR	Waterborne zinc silicate	flat panels	blasting	161	61	100	1
N	Temazinc 99	solvent borne zinc rhich epoxy	flat panels	blasting	133	53	80	1
O	Temasil 90	solventborne ethyl zinc silicate	flat panels	blasting	134	49	85	1
P	Bridge system	solvent borne	flat panels	blasting	421	51	370	3
Q	Sprayed Zn	flame	flat panels	blasting			160	1
R	Sprayed Zn	light arc	flat panels	blasting			220	1
S	Zinga	solvent borne 1-c	flat panels	blasting	204	44	147	2
T	ZingAlu	solvent borne 1-c	flat panels	blasting	218	80	138	2
U	Aquazinga	Waterborne zinc silicate	flat panels	blasting	193	72	121	2

Figure 28. *Samples mounted under road fencing at state highway 40,*

Figure 29. *Samples mounted at Bohus-Malmön,*

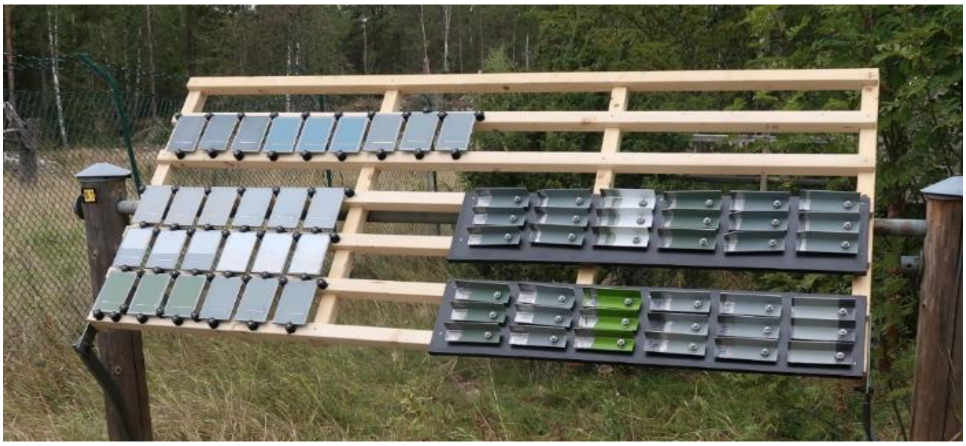

Figure 30. *Samples mounted in Ryda*

11.4 Inspection results after 32 months

The exposure on Bohus-Malmön was started on the 17th of September 2019. The exposure at Ryda station was started on the 16th of September 2019 and the exposure by the highway in Borås was started on the 19th of September 2019.

All sample specimens were inspected after approximately two years of field testing. One of the coating products, ZingAlu on blasted steel exposed at Bohus-Malmön have deteriorated prematurely. All other samples that has been inspected showed no corrosion damage.

A second inspection of the samples exposed at Bohus-Malmön was made on the 22nd of may 2022 after 32 months. Premature coating failure was noted both on Zinga and ZingAlu samples. Coating degradation was found exclusively on the steel side of the flat specimens. The inspection results showed that all other coating systems gave adequate corrosion protection for 32 months in a corrosivity described as C5 for steel and C3 for zinc. At this point, a full destructive assessment of the samples was deemed not meaningful because most samples were virtually unaffected by corrosion. Pictures of the samples can be found in Appendix A. ***Figure 31*** and ***Table 5*** shows the results of the pre-exposure pull-off adhesion and cross cut tests.

HDG-coatings usually have a very long life span in atmospheric conditions and coating systems used for repairing or refurbishing HDG steel should also have a long life to protect the steel in an optimal way. It is therefore impossible to perform natural corrosion testing of zinc rich coatings within a three year research project. The natural corrosion testing will continue after the project is formally ended. The progress of the sample deterioration will be followed yearly to assess the life span of the coating systems. When enough information has been gained from the corrosion testing the project will perform evaluations of the coating systems and publish the result in a written report containing estimates of the expected service life of the studied methods.

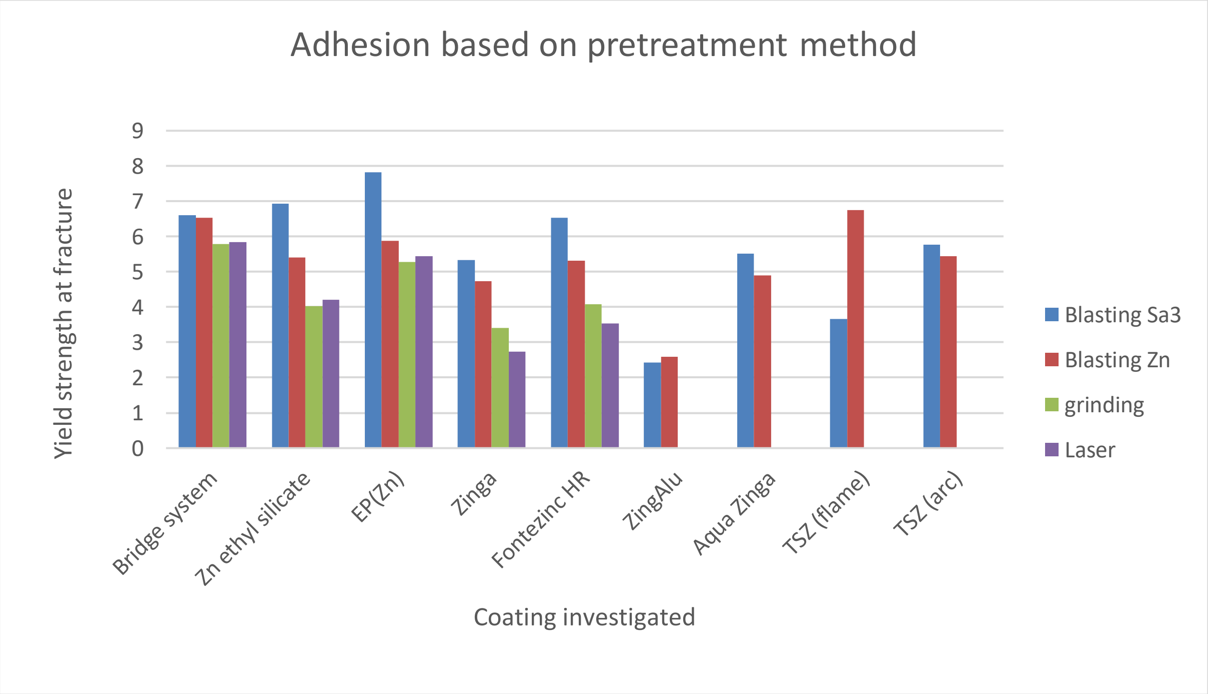

Figure 31. *Graphical representation of table 6 describing adhesion depending on substrate and pretreatment method for various types of coatings. Clean blasted steel gave best adhesion. Light blasted HDG gave lower adhesion compared to steel, while laser cleaning and grinding gave comparable adhesion on old HDG steel.*

Table 5. *Adhesion values for test panels using pull-off testing according to ISO 4628 (two pull-offs per sample) and cross cut-test according to ISO 2409 (two tests per sample). Adhesion for each coating has been evaluated with different pretreatment methods, Abrasive blasting on a new HDG coating with non-metallic abrasives to Sa3 according to ISO 8501-1 (denoted Blasting Sa3), light blasting/ profiling on new HDG coating using non-metallic abrasives (denoted: Blasting Zn), hashed grinding with a slow rotating P36 disc on an old HDG coating to achieve an even metallic sheen (denoted: Grinding Zn) and Laser cleaning with a 100W laser on an old HDG coating to achieve a dull grey appearance (denoted: Laser Zn)*

Coating	Substrate	Pull-off MPa	Cross-cut test	Pull-off MPa	Cross-cut test
Bridge system	Blasting Sa3	5,48	n/a	7,72	n/a
	Blasting Zn	7,57	n/a	5,50	n/a
	Grinding Zn	8,44	0	3,15	0
	Laser Zn	7,41	0	4,29	0
Zn ethyl silicate	Blasting Sa3	5,47	n/a	8,39	n/a
	Blasting Zn	5,81	n/a	5,00	n/a
	Grinding Zn	4,58	0	3,47	0
	Laser Zn	5,50	0	2,92	0
EP(Zn)	Blasting Sa3	8,02	n/a	7,62	n/a
	Blasting Zn	6,94	n/a	4,80	n/a
	Grinding Zn	5,06	0	5,48	0
	Laser Zn	5,32	0	5,58	0
Zinga	Blasting Sa3	5,97	n/a	4,69	n/a
	Blasting Zn	4,96	n/a	4,52	n/a
	Grinding Zn	4,40	1	2,40	0
	Laser Zn	2,56	1	2,92	0
Fontezinc HR	Blasting Sa3	6,82	n/a	6,25	n/a
	Blasting Zn	6,56	n/a	4,08	n/a
	Grinding Zn	4,45	0	3,71	0
	Laser Zn	3,80	0	3,28	0
ZingAlu	Blasting Sa3	2,32	n/a	2,52	n/a
	Blasting Zn	2,41	n/a	2,76	n/a
Aqua Zinga	Blasting Sa3	5,42	n/a	5,60	n/a
	Blasting Zn	5,21	n/a	4,60	n/a
TSZ (flame)	Blasting Sa3	2,38	n/a	4,95	n/a
	Blasting Zn	7,76	n/a	5,73	n/a
TSZ (arc)	Blasting Sa3	5,88	n/a	5,65	n/a
	Blasting Zn	5,66	n/a	5,23	n/a

12 Reference object inspections

Five different coating systems have been investigated by inspection of reference objects. The emphasis has been on trying to find reference objects that are well documented and that have been coated a long time ago. The study has focused mainly on zinc-rich coatings, with special interest in zinc-rich coatings that have been used as stand-alone systems, i.e. without any topcoat. Such coating systems can increase the applicability and ease of use as repair or refurbishment systems for HDG-steel structures. The references used in the study includes coating systems applied on low alloyed steel. The performance of coatings on steel is important for any coating used to repair HDG-steel. The results from the reference inspections is available in a separate report. [1] Some of the highlights from the report are as follows:

The breakdown mechanism of a coating can be very important when considering the corrosion protection of an asset from a life cycle perspective. It is evident that all the zinc-rich coatings studied deteriorated from the outside and in rather than via under-rusting and flaking. This mode of breakdown can be very advantageous, it means that the assets can be spot repaired to a higher extent than if they were protected with a coating system that deteriorates via flaking and loss of adhesion. A relatively easy and ad hoc maintenance protocol for single layer zinc-rich coating systems can reduce the need for downtime and secondary cost for maintenance of the asset.

It was hard to find any older and well documented refurbishments of HDG-steel to inspect within the framework of this study. The project did however identify a number of such installations. Initially an inspection trip including inspections of refurbished hot dip galvanized steel was planned, and the project leadership was invited to visit Induron in Alabama to inspect some of their reference objects coated with induraguard. During the visit we had planned to meet with the asset owners to some of the old refurbished steel structures. The project leadership was also invited to partake in inspections of a power transmission tower refurbishment performed with Zinga for Statnett in Norway. Unfortunately these reference trips was never carried out due to lock downs following the Covid-19 pandemic. In place of the inspections. Meetings with the asset owners have been held via teams and mail and the outputs from these meetings are detailed below.

12.1 Contact with asset owners and maintenance providers

The literature study that was performed prior to this project showed that corrosion of HDG steel can be a problem. Refurbishments of power transmission utilities is an elaborated business in USA, New Zealand and in the United Kingdom. Refurbishments of HDG power transmission towers is extremely challenging and it is of interest to this project to share experience and get insights into how different owners tackle their corrosion problems. One aim of this project has therefore been to establish a contact with asset owners that regularly perform maintenance of their HDG steel. Some of the results have been included in the following section.

12.1.1 Transpower New Zealand

Transpower is the infrastructure provider that handles power transmission and distribution in New Zealand. Being an island in the pacific, New Zealand has a very different climate compared to Sweden. The corrosivity on the island varies a lot with location, and land based assets are placed in environments that ranges from benign to extreme corrosivity. Transpower has a dedicated maintenance team and maintenance program that includes regular inspections of all of their assets. They have elaborated an inspection methodology that classifies their HDG steel constructions into different classes of corrosion decay. The classification system is used to plan for future inspections and maintenance of their power transmission towers. According to the maintenance team, it is very important to carry out refurbishments with the right timing in order to get an economically sound maintenance program. Transpowers asset portfolio includes unpainted HDG towers that have a life expectancy of about 15-150 years from installation to the first refurbishment. Refurbishment methods used have a life expectancy of 5 – 25 years depending on the location of the asset. The current maintenance plan includes refurbishments by blasting and painting of about 400-450 towers per year.

Tower painting is mainly carried out with vinylic coatings, but Transpower have also trialed zinc-rich coatings. In an effort to exchange knowledge, the maintenance team of Transpower have shared the complete refurbishment programme including corrosion assessment methods and key recoat factors used to plan refurbishments of power transmission utilities with their Swedish counterpart at Swedish powergrids. Transpower has also communicated rough estimates of the cost for refurbishments and newbuilds, see ***Table 6***

Table 6. *Approximate cost for new installation, first refurbishment and secondary refurbishments for power transmission towers in New Zealand.*

Type of structure	**New installation [k NZD]**	**First coat [k NZD]**	**Recoat [k NZD]**
Small power transmission tower, 230-280 m^2	200-250	170	50
Large power transmission tower 1000 m^2	400-450	160-180	120-140

12.1.2 Power transmission tower maintenance in USA

In USA there appears to be a well evolved infrastructure of entrepreneurs that perform maintenance of galvanized steel. For example, Public Utilities Maintenance Incorporation is one organisation, the following can be read at their webpage:

PUM Inc. is a painting/corrosion control contractor specializing in painting of high voltage steel lattice electrical transmission towers, tubular steel transmission poles, telecommunication towers, light poles, power substation structures, power generation structures, and similar elevated complex structures … Since 1992, we have safely and successfully painted over 70,000 steel transmission towers and poles of voltages ranging from 69kV to 765 kV… Over 90% of the transmission structures were energized during painting operations.

Curt Hicox, a co-worker at Public Utilities maintenance Incorporation has extensive experience of coating work on galvanized steel structures. His view is that power transmission assets have to be maintained simply because there are so many of them. Galvanized lattice power transmission towers are typically designed for technical lifetime of about 80 to 100 years, however, according to Hicox, the practical life of such structures tend to be about 40-50 years on average of the population of lattice towers built in the US. The expected practical life depends on the location and the corrosivity where the towers are built. In USA and Canada there is about 1 million transmission towers and poles.

According to Hicox, it would be impossible to replace them, both from a cost standpoint and because of logistical constraints. For many years it has been the practice in the US, as well as in Canada and many other countries, to perform transmission structure corrosion-related maintenance and repair. Depending on structure size, a crew can normally paint more than one tower a day. This equates to direct costs of repainting a structure that are just a fraction of the costs to replace, and the savings of the logistical costs relating to time, outage requirements and environmental impact for replacing are even more significant.

One important factor for corrosion mitigation of worn out steel structures appears to be the timing of the maintenance. If a structure is maintained when it is about 50% rusted the total cost for refurbishment is typically 40 % higher compared to what it would have been if the maintenance was performed at a stage where the steel was only 5% rusted [20] [21]. This difference can be attributed to a much more costly pretreatment and need for duplex coating systems on steel that is heavily corroded. If the galvanized steel is maintained before all zinc is consumed, the refurbishments can be performed with minimal pretreatment and a single coat paint application. The cost for recoating is about 10 000 USD for a tower that costs about 200 000 USD to build.

Years ago a coating technology was developed that afforded long term, cost effective protection to weathered, moderately corroded galvanized steel towers and poles. A single coat, hand applied (not sprayed) to minimally prepared (hand tool cleaned) moderately rusted galvanized steel transmission and substation structures provides approximately 25 years of protection when exposed to non-coastal, moderate atmospheres. The Keeler & Long PPG 4400 Series was the original coating developed for this application back in the 1950's, however other manufacturers such as Induron Protective Coatings with their 9200 Induragard Tower Coating are also widely used. As a result of continuous contact with Induron, this project has contributed to the establishment of an agreement between Induron and AB Röa who have become a retailer of the Induron products in Sweden.

12.1.3 Statnett of Norway

Statnett of Norway has recently invested in refurbishments of two power transmission towers. The towers are about 70-80 years old and are placed in an industrial area located close to the sea. The corrosivity at the location has probably been relatively high due to a combined effect of the sea and the industrial atmosphere. The steel in the towers showed spot-wise complete consumption of the HDG-coating with accompanying red-rust and development of pack rust. The towers are placed within a factory facility with sensitive surroundings and the towers are the only point of power supply to the factory. The chosen refurbishment method included scaffolding and a full cover-up with plastic containment to protect workers and the sensitive surroundings from contamination of blasting media and overspray. All steel members of the towers were wet blasted with a slurry of abrasives and water containing Chlor-rid. After abrasive blasting, the steel was coated with Zinga 2x90µm. The application technique used was airless spraying. The work was carried out up to about half of the height of the towers while power was transmitted. The line arms and the top of the towers were treated with the power off. Feedback from Statnett is that the wet abrasive blasting technique created too much vapor inside the containment which made visibility during blasting a problem. The second tower will be sandblasted with traditional dry methods. The cost of the refurbishment was about the same as a new build. Several factors, including access to the towers, power supply demand and limited space for a new build was key to the choice of refurbishing the towers instead of replacing them.

12.1.4 Swedish HDG asset owners

Some Swedish infrastructural assets are purchased with requirement specifications that rely on an additional domestic annex in the SS EN ISO 1461 standard for HDG-coatings. For example, HDG steel ordered for power transmission utilities owned by Swedish powergrids are often required to be coated with no less 95 µm, however, it is not uncommon that the actual coating thickness significantly exceeds the 95 µm requirement. The Swedish road administration uses a requirement of minimum 115 µm. Both the Fe/Zn 115 and the Fe/Zn 95 requirements constitute a considerable thickness and life expectancy increase compared to the general European norm of 85 µm. Both Swedish powergrids and the Swedish Road Administration have reported that general atmospheric corrosion of HDG steel is not currently a problem. Today, atmospheric HDG steel along roads and powerlines is usually replaced for other reasons than corrosion.

13 Proposed repair methods

The results of the investigations from the previous sections allows the below recommendations for repair methods to be made. These recommendations can be used by asset owners during maintanenace planning and procurement.

13.1 Small damage on new HDG steel

- If the corrosivity is low, C3 (for zinc) or lower, small damages can be left unattended provided that they are not located in safety critical areas of the steel structure.

If small damages shall be repaired, any of the following can be recommended:

- Washing, grinding with abrasive paper, brush painting with waterborne zinc silicate

- Washing, blasting to Sa3, and coating with thermally sprayed zinc or Zn/Al
- Washing, blasting to Sa2½, and painting with a zinc-rich coating product

13.2 Refurbishments of complete steel structures

Complete refurbishment of HDG steel structures with worn out corrosion protection may be refurbished by any of the following:

- The Induron method (see section 9.6)
- Wet abrasive blasting followed by painting with vinyl coating
- Wet abrasive blasting followed by painting with zinc-rich coating
- Dry abrasive blasting to Sa3, followed by coating with thermally sprayed zinc or Zn/Al

14 LCA of proposed repair method

An LCA study according to the relevant standards, comprising climate impact and ozone formation potential has been carried out within this project and is available in a separate report. [22] This section gives a brief summary of the results from the LCA study. The results are compiled graphically in ***figure 29*** and ***30***. The results in ***figure 29*** and ***30*** depict the environmental burdens from one occasion of refurbishment compared with one new-build. However, the expected life extension of the different refurbishment methods are different. Both the life extension and the expected life of a new build, (the base-case) will differ depending on the corrosivity where the asset is placed during service. To get a different picture of the same results ***Figure 31*** and ***32*** depict the number of refurbishments that can be performed to reach a breakeven point for the environmental burdens. In other words, how many times can a specific refurbishment be performed before it becomes environmentally more beneficial to rebuild the structure instead of refurbishing it.

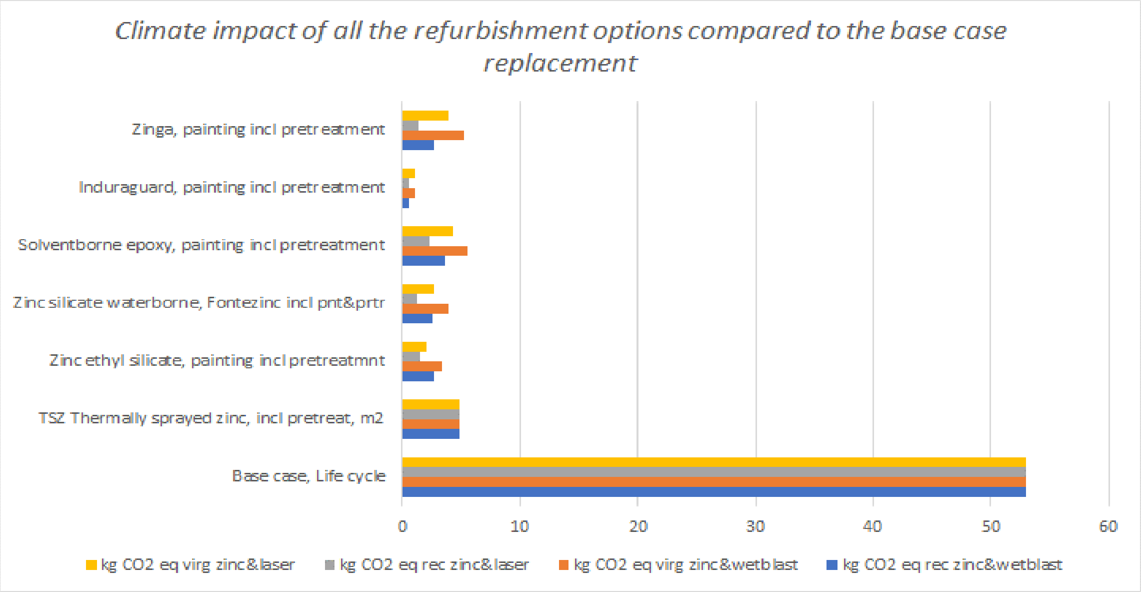

Figure 32. *Results from the LCA showing the amount of CO2 equivalents for the base-case and one refurbishment for each refurbishment method The refurbishment methods include both various pre treatment methods and different results depending on the source of zinc, recycled or virgin zinc.*

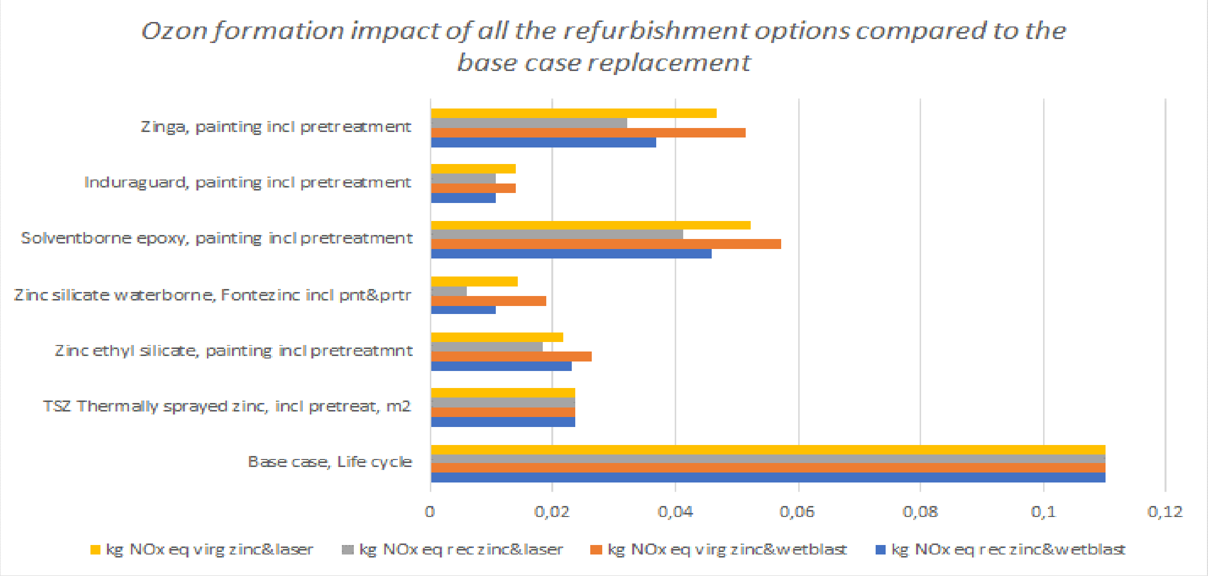

Figure 33. *Results from the LCA showing the amount of smog forming potential or NOx equivalents for the base-case and one refurbishment for each refurbishment method The refurbishment methods include both various pretreatment methods and different results depending on the source of zinc, Recycled or virgin zinc.*

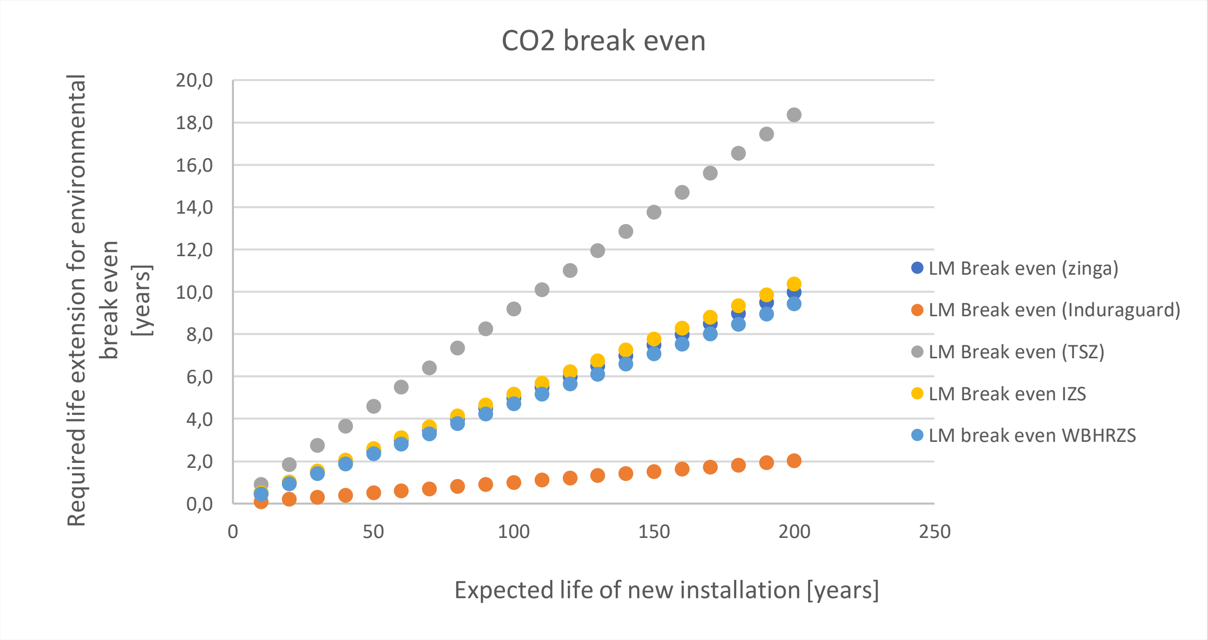

Figure 34 *The graph shows the minimum required life extension (in numbers of years) that each refurbishment method has to prolong the service life of the asset in order to be beneficial, (in terms of CO2-footprint). The required life extension is linearly dependent on the base-case life expectancy of the base-case, (x-axis).*

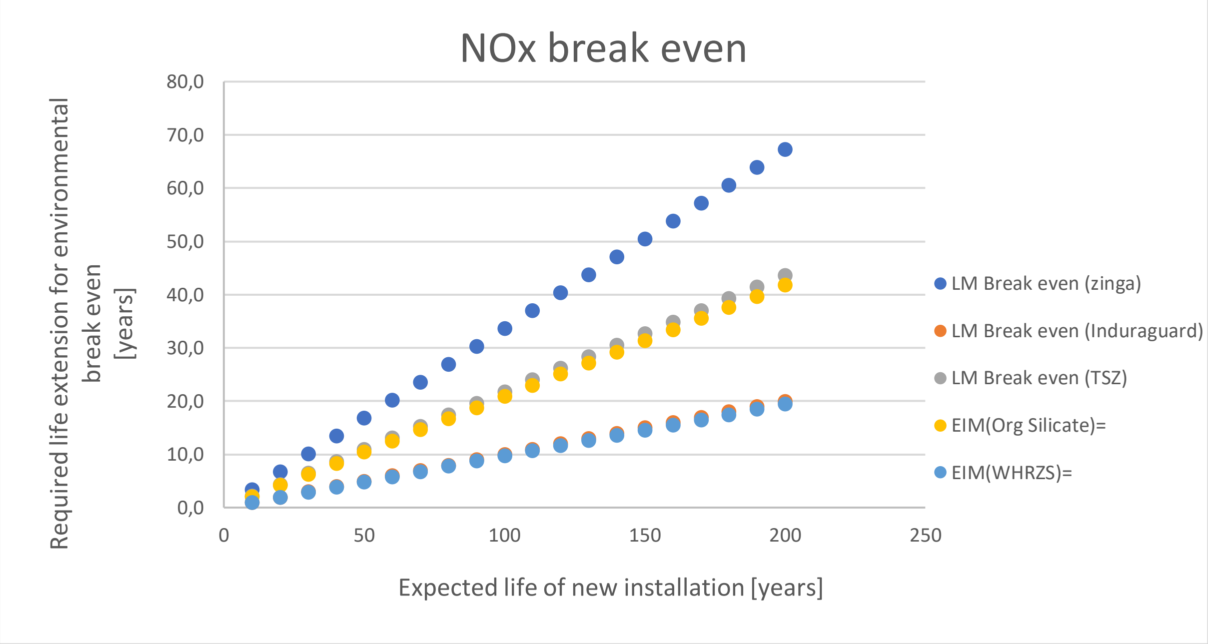

Figure 35 *The graph shows the minimum required life extension (in numbers of years) that each refurbishment method has to prolong the service life of the asset in order to be beneficial, (in terms of CO2-footprint). The required life extension is linearly dependent on the life expectancy of the base-case, (x-axis).*

14.1 Conclusions from LCA study

Pretreatment using blasting is a large contributor to the overall environmental footprint. This can be reduced by using laser cleaning to prepare the surface. Laser cleaning also reduces the amount of hazardous waste. The LCA model includes virgin zinc for TSZn and HDG steel. Zinc in coatings may come from zinc dross, recycled from galvanizing plants and many zinc coatings are based on recycled zinc. The zinc origin has a significant factor in the LCA and hence for the resulting environmental footprint. Thermally sprayed Zn and zinc silicates are good options where blasting is possible. Without blasting possibilities, Induraguard 9200 appears to be an interesting alternative. To minimize the NOx emissions, it is important to reduce pretreatment by blasting and to use coating products with low VOC, alternatively to use coating products formulated with VOC with low smog forming potential. Typical solvents that give high smog forming potential are aromatic solvents such as xylene and toluene.

15 LCC case study

Refurbishment of complex HDG structures such as power transmission towers is not normally performed in Sweden. It is therefore hard to get an accurate quote for what a typical refurbishment will cost before a business infrastructure of dedicated maintenance entrepreneurs has been established. Conswquently it is more interesting to compare the price of actual refurbishment jobs that have been performed elsewhere, where such maintenance entrepreneurs exists. In the following case study, we have summarized price estimations of the different methods studied in this research report. Cost estimations are based on actual cases for different methods used in New Zealand, USA and Norway, see section 12. Technical lifetime of refurbishments play an important role in the overall LCC. Life extensions for the various methods are based on experience from Induron and PUMINC (USA), as well as the reference object inspection and corrosion testing reports completed as part of this research study. [15] [1] The results presented here are estimations of refurbishments of power transmission towers, the actual costs of a real refurbishment project will depend on the specific steel structure and its accessibility. It should be mentioned that refurbishments on more accessible objects such as street lamp posts or handrails is likely to have higher economical potential using blasting as pretreatment. Below we have compiled a list of considerations that will affect the cost of a refurbishment.

Basic considerations

- The cost for each refurbishment of a specific HDG asset depends on location, accessibility, and complexity of the structure.
- The choice of pretreatment method is important and will be directly mirrored in the total maintenance life cycle cost.
- An important consideration when choosing a maintenance program is the life expectancy of the maintenance method and the life expectancy of the base case, i.e. a new HDG steel structure.
- The life expectancy for both refurbishment and steel exchange depends on the corrosivity at the location where the asset will be used.
- Given a specific pretreatment method, we know from earlier studies [23] that the price for the coating product does not significantly affect the overall price for each maintenance job.

15.1 Refurbishment with scaffolding and dry abrasive blasting

Statnett has reported that the cost for full containment, washing and abrasive blasting followed by two coat application with a zinc-rich coating was roughly as expensive as a replacement with a newly built HDG tower. In this context, we can assume a refurbishment cost of 100% of the base case for a refurbishment consisting of scaffolding, containment, blasting and two coats of paint.

15.2 Refurbishment without scaffolding and vinyl coatings

From our discussion with Transpower we have some indicative costs for newbuilds and refurbishments, see ***Table 6***. These costs have been elaborated to account for a fictive maintenance program where the practical life of the asset is doubled see ***Table 7***. The average cost of refurbishing for each recoat has been calculated in ***Table 8***. This gives us a cost estimate that can be used to compare maintenance costs with the other refurbishment methods. We can assume that each pretreatment by partial containment and wet abrasive blasting/ slurry blasting costs around 35% of the base case.

Table 7. *Approximate cost for new installation compared with refurbishment cost for power transmission towers in New Zealand*

Type of structure	**New installation [k NZD]**	**Number of coats**	**Life span w/o Maintenance [years]**	**Expected life of coating [years]**	**Life span with maintenance [years]**	**Cost of maintenance [k NZD]**
Small tower 230-280m2	200-250	1:st coat 2 recoats	15	5	30	270
Large tower 1000m2	400-450	1:st coat 2 recoats	15	5	30	400-460
Small tower 230-280m2	200-250	1:st coat 2 recoat	60	20	120	320
Large tower 1000m2	400-450	1:st coat 2 recoats	60	20	120	520-600
Small tower 230-280m2	200-250	1:st coat 3 recoat	100	25	200	320
Large tower 1000m2	400-450	1:st coat 3 recoats	100	25	200	520-600

Table 8. *Approximate cost for new installation, first refurbishment and secondary refurbishments for power transmission towers in New Zealand. The last column is an estimation of average cost per refurbishment expressed as present of a new installation, which is defined as the base-case in our LCA study*

	New installation [k NZD]	**First coat [k NZD]**	**Recoat [k NZD]**	**# refurbishments**	**Average Cost/ refurbishment % of newbuild**
Small tower 230-280 m2	200-250	170	50	1+2	36-45%
Large tower 1000 m2	400-450	160-180	120-140	1+2	30-35%

15.3 Refurbishment with induragard

From our discussions with Induron, and Public Utility Maintenance Inc we have information that recoating a power transmission tower without containment or pretreatment using one coat of Induraguard costs about 10 000 USD for an intermediate sized 200 000 USD power transmission tower. 10 000 USD equals about 7% of the base case for a small power transmission tower as per Transpowers example, or about 4% for a large tower. We can therefore estimate that the cost for refurbishment without pretreatment, scaffolding or containment is about 5% of the base case.

15.4 Summary of cost estimates

In this context, it is immediately clear that scaffolding and containment is a major cost driver for complete refurbishments of power transmission towers. A second cost driver is the choice of pretreatment method and number of coats that must be applied. From earlier LCC studies on recoating bridges we know that the cost for paint is about 2% of the total LCC costs of a bridge maintenance program. If we assume similar cost for paint applied to power transmission towers, we can disregard the comparatively small price differences between different coating products. However, the choice of coating product has a big impact for the expected maintenance cost because different products require different pretreatments. In ***Table 9*** rough cost estimates depending on maintenance methods have been indicated, the table also indicates which maintenance methods that can be used with which coating products.

Table 9. *Rough estimations of cost compared to the base case (steel structure exchange). According to experience from PUM Inc. (USA), Transpower (NZ) and Statnett (NOR).*

Maintenance method	HDG 80µm	Zinga 120µm	IZS 90µm	WBHRZS 90µm	TSZ 100µm	Vinylic	Induragard 200µm
RebuildBase case Cost [% of base case]	100%						
Full containment, blasting Cost [% of base case]	n/a	100%	100%	100%	100%	100%	n/a
Partial containment, wet blasting Cost [% of base case]	n/a	35%	50%	50%	n/a	35%	n/a
No containment no blasting Cost [% of base case]	n/a	n/a	n/a	n/a	n/a	n/a	5%

Note: Green cost assumptions are based on cost from real refurbishment projects, orange costs are estimates based on similar refurbishment methods and the assumption that pretreatment is the main cost driver for refurbishments, it is estimated that zinc silicates (IZS and WBHRZS) require more thorough blasting compared to Zinga and vinylic coatings, hence the slightly higher cost . Yellow cost assumptions is 100% for the base case by definition. n/a means that the indicated pretreatment method is not recommended for the indicated product.

15.5 Expected life

The perhaps most important factor in establishing a valid life cycle cost (LCC) analysis for protective coatings is to have a correct estimation of the expected life of the protection. In this analysis, we have based the life expectancy as much as possible around real installations and experience, see Table 10. The life expectancy of vinylic coatings is based on experience from Transpower of New Zealand. With 400-500 refurbishments per year they have extensive experience from the system. The life expectancy of Induraguard 9200 is based on experience from the US where about 5000 refurbishments are performed per year. Zinga and waterborne zinc silicates have been studied by both accelerated corrosion testing and via reference object inspections. These studies indicate that zinga and zinc ethyl silicates will have a life of at least 30 years and 50 years respectively in the indicated corrosivity class. In addition, the AS/NZS 2312: 2002 standard indicates that waterborne silicates have longer life than HDG and that zinc ethyl silicates have an expected life that is roughly half that of HDG steel. Thermally sprayed coatings are expected to have slightly shorter service lives compared to HDG but they are usually applied in somewhat higher thickness, which makes the two types of coatings equal in terms of expected service life. We do not have any long term data available for stand-alone zinc epoxies and we have therefore chosen to omit it from this LCC. The field exposures started within this project are still ongoing and the plan is to evaluate the samples intermittently to be able to update the life expectancies when new information is available.

Table 10 *Expected life extension of refurbishment of power transmission towers placed in an environment described as C2 for steel and C3 for zinc. Estimates of expected life extensions are according to experience from Induron/ Alabama Power, the reference object inspection and corrosion testing reports performed as part of this research study (RISE ref).*

	HDG 80µm	Zinga 120µm	IZS 90µm	WBHRZS 90µm	TSZ 100µm	Vinylic	Induragard 200µm
expected life [years]	100	30	50	100	100	25	25

Note: Green life expectancies are based on experience from real refurbishment projects. Orange estimates are rough estimates based on reference object inspections and corrosion testing. Estimation in red is based on the AUS/NZ standard that estimates waterborne zinc silicates to be at least as long lived as HDG. Yellow life expectancies are based on zinc corrosion rates corresponding to C3 for zinc.

15.6 LCA and LCC summary

Building on the framework of estimated refurbishment costs, expected life, and LCA results for the various refurbishment methods we have made an effort to compile a holistic summary of HDG refurbishment, see ***Table 11*** and ***Figure 36***. The figure shows expected costs and climate impact reduction of refurbishing and thereby doubling the life of an existing steel structure with worn out corrosion protection. Depending on the refurbishment method, a different number of refurbishments will be required in order to double the service life of the given asset. The number of refurbishments are also important because it gives a hint at the amount of logistics needed for a complete maintenance program.

Table 11 *Summary of expected costs and life expectancies for various maintenance methods of a HDG steel structure placed in an environment corresponding to C2 for steel and C3 for zinc.*

	HDG 80µm	Zinga 120µm	IZS 90µm	WBHRZS 90µm	TSZ 100µm	Vinylic	Induragard 200µm
Cost [% of base case]	100%	35%	50%	50%	100%	35%	5%
Expected life [years]	100	30	50	100	100	25	25

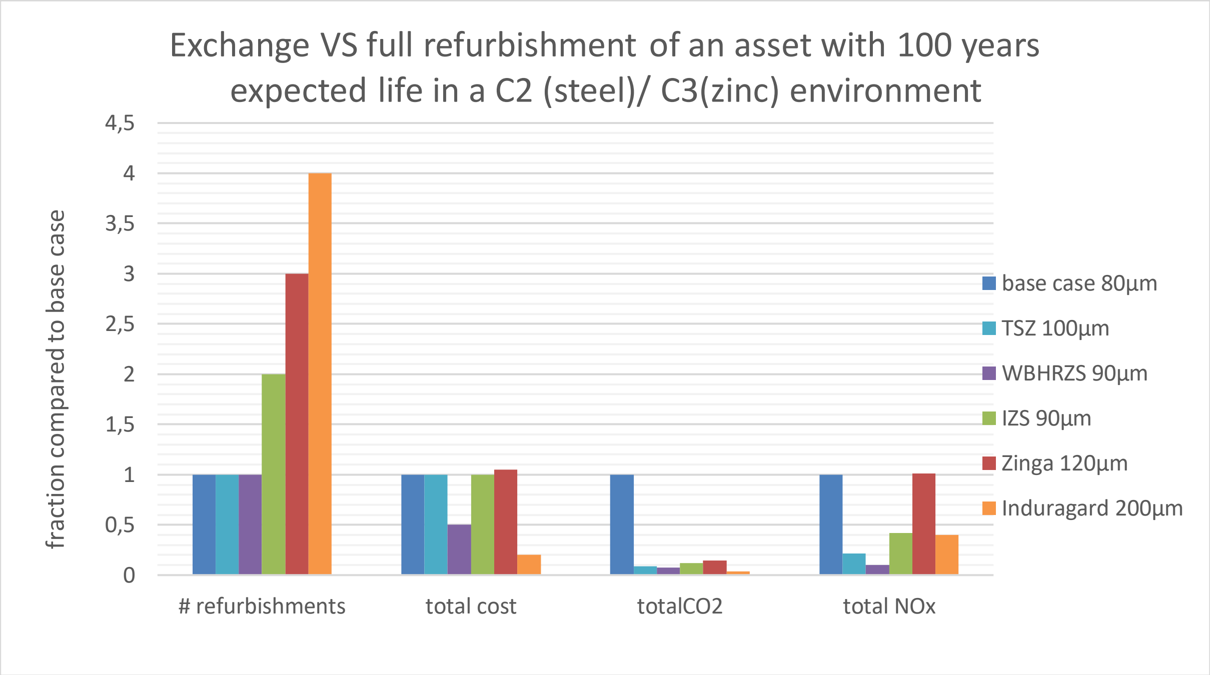

Figure 36 *Summary of estimated total maintenance, cost, climate and NOx footprint for refurbishing a HDG power transmission tower in C2 (steel) C3 (zinc) with an expected service life of 100 years .*

16 Discussion

This study aimed to make a holistic analysis of maintenance of hot dipped galvanized steel structures, and to investigate how, when and if a maintenance strategy should be undertaken.

Through our communication with Swedish powergrids and the Swedish road authorities we have learned that hot dip galvanized steel is usually not exchanged due to atmospheric corrosion, rather it is much more common that steel structures are replaced for other reasons, for example due to structural defects such as impact damage on road furniture, or due to rerouting or capacity increase by the power transmission companies. In this context it should also be mentioned that Swedish powergrids have an extensive maintenance programme for steel members buried in soil. But there are also examples where maintenance strategy for atmospheric corrosion of HDG may be beneficial, for example street lamp posts, radio masts and stay cables. In other countries, e.g. USA, New Zealand and UK, a methodology to maintain and refurbish hot dip galvanized steel is rather well established, particularly for power transmission towers.

A reason for the difference in maintenance strategy may be a relatively low corrosivity for zinc on infrastructural assets in Sweden. The corrosivity for zinc in Sweden can often be assumed to be C3, which equals a corrosion rate of approximately 1 µm coating loss per year. It may also be due to higher demands on coating thickness and national addendums to the ISO standards used for hot dipped galvanized steel by Swedish authorities. The expected life of a HDG coating is thus about 100 years. In this context, it might well be that most of Sweden’s infrastructural assets still have some 30-60 years of technical life before they would need to be exchanged due to corrosion. If that is the case, it may be that this study was started well before a general problem has formed. On the other hand, from our discussions with overseas asset owners, the timing of refurbishments appear to be crucial to build a cost effective maintenance program. In that sense, this study could be useful for starting such maintenance program before it is too late, or before the logistics for such a program become impractical. During the project we have also had contact with several asset owners who are interested in pursuing a maintenance program for HDG steel in order to proactively prevent a situation where an ageing infrastructure becomes logistically challenging.

The corrosivity of zinc can be very local and different parts of the same structure may show very different corrosion rates. For a HDG structure with expected life of 100 years it is not unlikely that coating loss on corrosion hot-spots could consume all the coating in around 10 to 15 years. This fact makes repair methods or partial refurbishments of hot dip galvanized steel interesting. It is also common that hot dip galvanized steel gets damaged during transport and structure assembly. Such damages may, depending on the corrosivity and damage location need to be repaired to comply with the intended design life of the structure. How to best repair HDG structures have also been a focus of this study. We have divided maintenance work into two categories, complete refurbishments and repairs.

Refurbishment of HDG steel structures with worn out corrosion protection may be refurbished by:

- The Induron method
- Wet abrasive blasting followed by painting with vinyl coating
- Wet abrasive blasting followed by painting with zinc rich coating
- Dry abrasive blasting to Sa3, followed by coating with thermally sprayed zinc or Zn/Al

If the corrosivity is low, C3 (for zinc) or lower, small damages can often be left unattended provided that they are not located in sensitive areas of the steel structure.

If small assembly damages or corrosion ot-spots shall be repaired, the following methods can be recommended:

- Washing, grinding with abrasive paper, brush painting with waterborne zinc silicate
- Washing, blasting to Sa3, and coating with thermally sprayed zinc or Zn/Al
- Washing, blasting to Sa2½, and painting with zinc rich coating product

The life cycle analysis, LCA that has been performed as part of this project, clearly indicates that refurbishments gives much less environmental impact compared to structure exchange. To minimize the environmental impact of a single refurbishment, preferred coatings should require minimal pretreatment and be formulated with low VOC, or with VOC that has a low smog formation potential.

The approximate costs that have been used in the life cycle cost analysis come from experience from power transmission asset owners abroad. It is clear that in order to limit the cost of refurbishment, the used coating should require minimum pretreatment, and the coating work should be performed without scaffolding or containment in order to be economical. The life cycle cost analysis shows that most of the methods studied can be cheaper than compared to exchanging the structure. However, a maintenance program can become logistically challenging, especially when the business chain for such maintenance work is not in place.

The most important factor for LCA analysis of protective coatings, is the expected service life of the treatment. The corrosion testing performed in this project has not been completed and a precise life expectancy from the various methods studied is not yet available. The corrosion testing will be followed closely and the results will be updated yearly. In lack of precise life expectancies we have used approximate life expectancies for the various methods. The life expectancies used in the LCA are based on reference object inspections, experience from power transmission asset owners abroad and the AU/ NZ standard.

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18 Referenced standards

ISO 1461 Hot dip galvanized coatings on fabricated iron and steel articles — Specifications and test methods

ISO 12944-5 Paints and varnishes - Corrosion protection of steel structures by protective paint systems - Part 5: Protective paint systems

ISO 12944-6 Paints and varnishes - Corrosion protection of steel structures by protective paint systems - Part 6: Laboratory performance test methods

ISO 12944-9 Paints and varnishes - Corrosion protection of steel structures by protective paint systems -Part 9: Protective paint systems and laboratory performance test methods for offshore and related structures

ISO 9226 Corrosion of metals and alloys -- Corrosivity of atmospheres -- Determination of corrosion rate of standard specimens for the evaluation of corrosivity

ISO 2808 Paints and varnishes -- Determination of film thickness

ISO 2178 Non-magnetic coatings on magnetic substrates - Measurement of coating thickness - Magnetic method

ISO 2063 Thermal spraying - Zinc, aluminium and and their alloys - Part 1: Design considerations and quality requirements for corrosion protection systems

ISO 3549 Zinc dust pigments for paints - Specifications and test methods

ISO 14713 -1 Zinc coatings - Guidelines and recommendations for the protection against corrosion of iron and steel in structures - Part 1: General principles of design and corrosion resistance

ISO 14713 -2 Zinc coatings - Guidelines and recommendations for the protection against corrosion of iron and steel in structures - Part 2: Hot dip galvanizing

ISO 8501-3 Preparation of steel substrates before application of paints and related products - Visual assessment of surface cleanliness - Part 3: Preparation grades of welds, edges and other areas with surface imperfections

ISO 4628-1 Paints and varnishes - Evaluation of degradation of coatings - Designation of quantity and size of defects, and of intensity of uniform changes in appearance - Part 1: General introduction and designation system

ISO 4628-2 Paints and varnishes - Evaluation of degradation of coatings - Designation of quantity and size of defects, and of intensity of uniform changes in appearance - Part 2: Assessment of degree of blistering

ISO 4628-3 Paints and varnishes - Evaluation of degradation of coatings - Designation of quantity and size of defects, and of intensity of uniform changes in appearance - Part 3: Assessment of degree of rusting

ISO 4628-4 Paints and varnishes – Evaluation of degradation of coatings – Designation of quantity and size of defects, and of intensity of uniform changes in appearance – Part 4: Assessment of degree of cracking

ISO 4628-5 Paints and varnishes - Evaluation of degradation of coatings - Designation of quantity and size of defects, and of intensity of uniform changes in appearance - Part 5: Assessment of degree of flaking

ISO 4628-6 Paints and varnishes - Evaluation of degradation of coatings - Designation of quantity and size of defects, and of intensity of uniform changes in appearance - Part 6: Assessment of degree of chalking by tape method

ISO 4628-7 Paints and varnishes - Evaluation of degradation of coatings - Designation of quantity and size of defects, and of intensity of uniform changes in appearance - Part 7: Assessment of degree of chalking by velvet method

ISO 4628-8 Paints and varnishes - Evaluation of degradation of coatings - Designation of quantity and size of defects, and of intensity of uniform changes in appearance - Part 8: Assessment of degree of delamination and corrosion around a scribe or other artificial defect

ISO 8501-1 Preparation of steel substrates before application of paints and related products - Visual assessment of surface cleanliness - Part 1: Rust grades and preparation grades of uncoated steel substrates and of steel substrates after overall removal of previous coatings

ISO 8502-6 Preparation of steel substrates before application of paints and related products - Tests for the assessment of surface cleanliness - Part 6: Extraction of water soluble contaminants for analysis

ISO 8502-9 Preparation of steel substrates before application of paints and related products - Tests for the assessment of surface cleanliness - Part 9: Field method for the conductometric determination of water-soluble salts

ISO 8502-3 Preparation of steel substrates before application of paints and related products - Tests for the assessment of surface cleanliness - Part 3: Assessment of dust on steel surfaces prepared for painting (pressure-sensitive tape method)

ISO 8503-2 Preparation of steel substrates before application of paints and related products - Surface roughness characteristics of blast-cleaned steel substrates - Part 2: Method for the grading of surface profile of abrasive blast-cleaned steel - Comparator procedure

ISO 4624 Paints and varnishes - Pull-off test for adhesion

ISO 2409 Paints and varnishes -Cross-cut test

NACE SP0315-2015/IEEE Std 1835-SG, Atmospheric (Above grade) Corrosion Control of Existing Electric Transmission, Distribution and Substation Structures by Coating Systems

NACE SP0215-2015/IEEE Std 1839-SG, Below-Grade Corrosion Control of Transmission, Distribution, and Substation Structures by Coating Repair Systems

NACE SP0415-2015/IEEE Std 1895-SG, Below-Grade Inspection and Assessment of Corrosion on Steel Transmission, Distribution, and Substation Structures

Appendix A

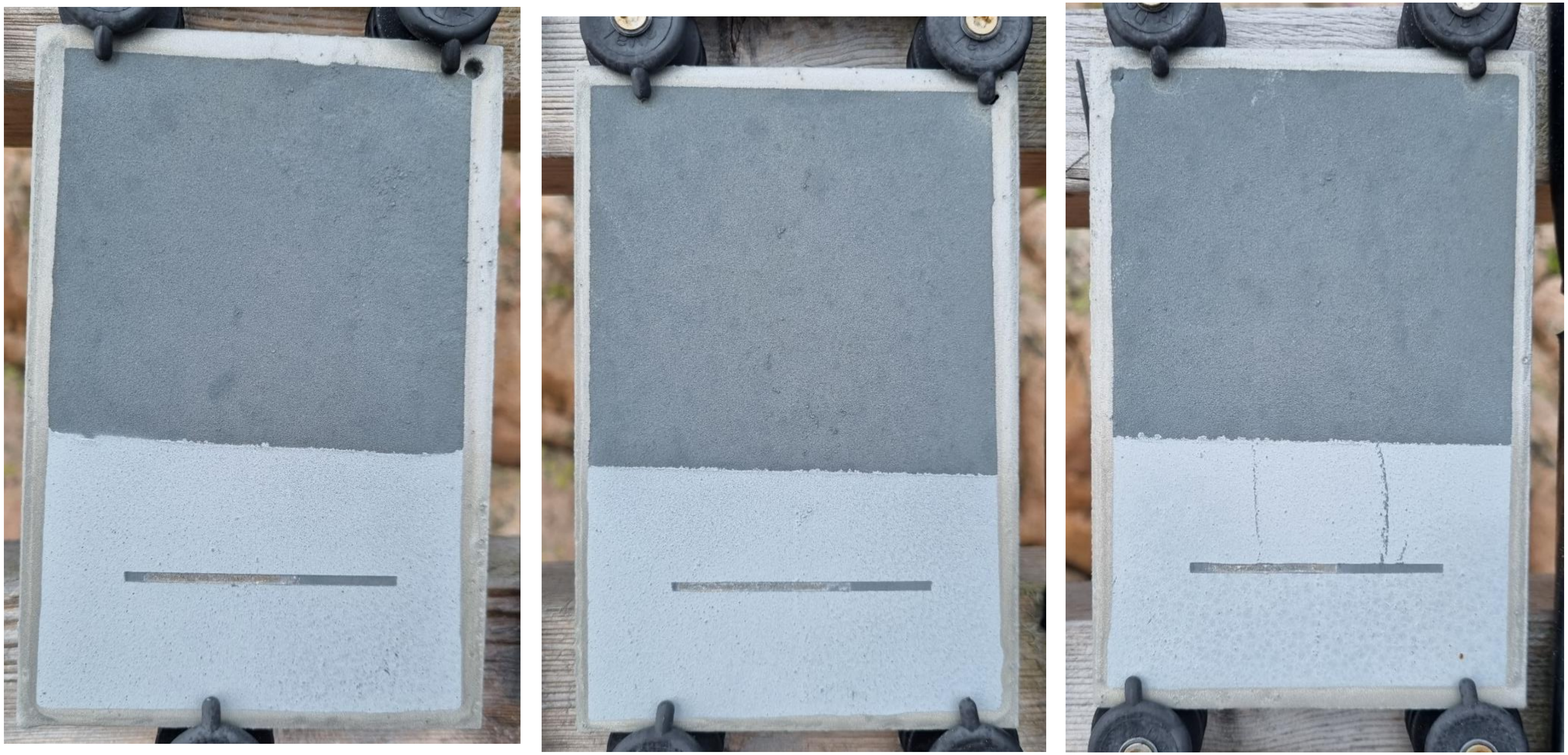

Figure 37. *System R, thermally sprayed zinc (TSZ) applied with flame spraying equipment, bottom half was seald with thinned epoxy.*

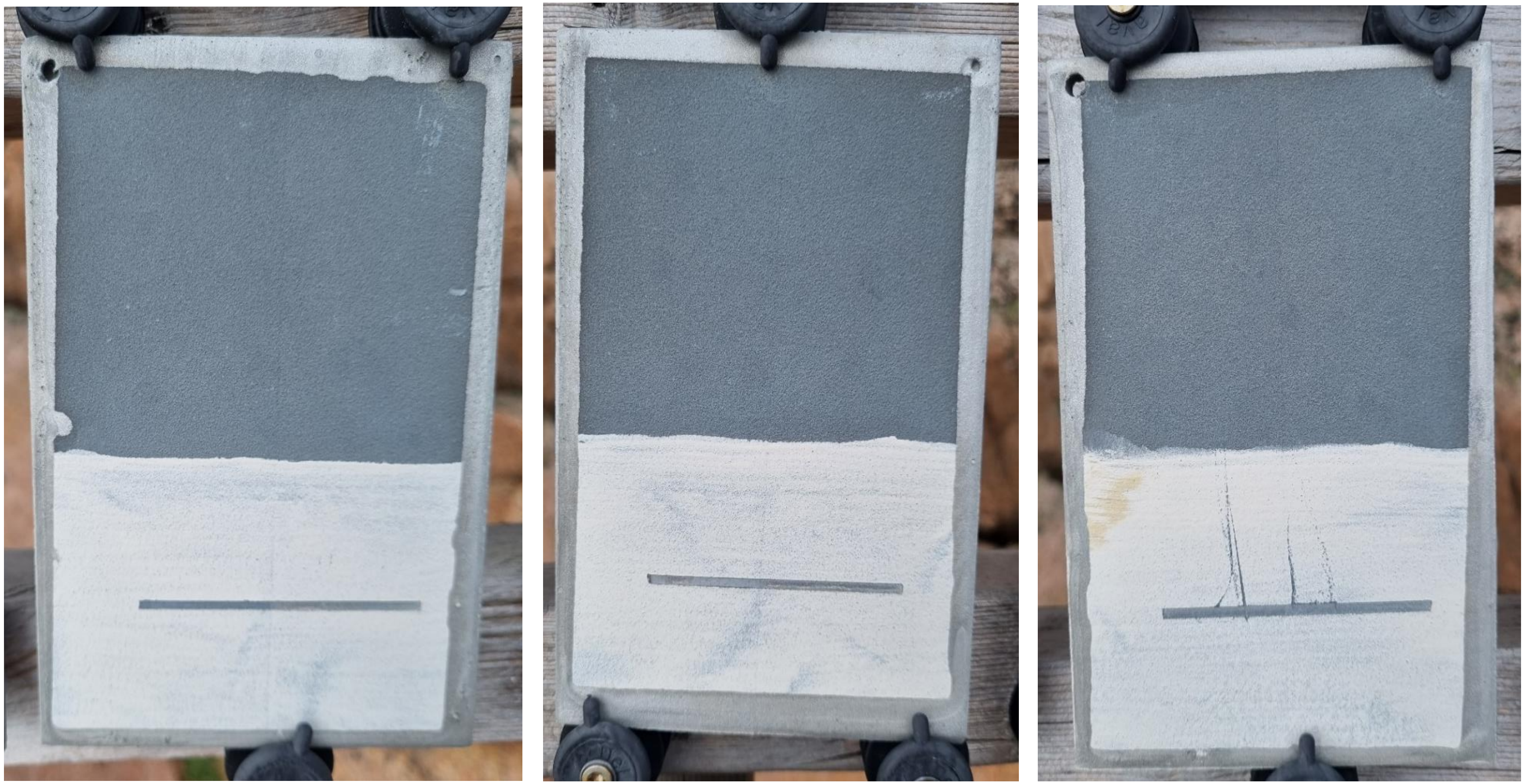

Figure 38 *System P, thermally sprayed zinc (TSZ) applied with arc spraying equipment, bottom half was seald with thinned epoxy using a brush.*

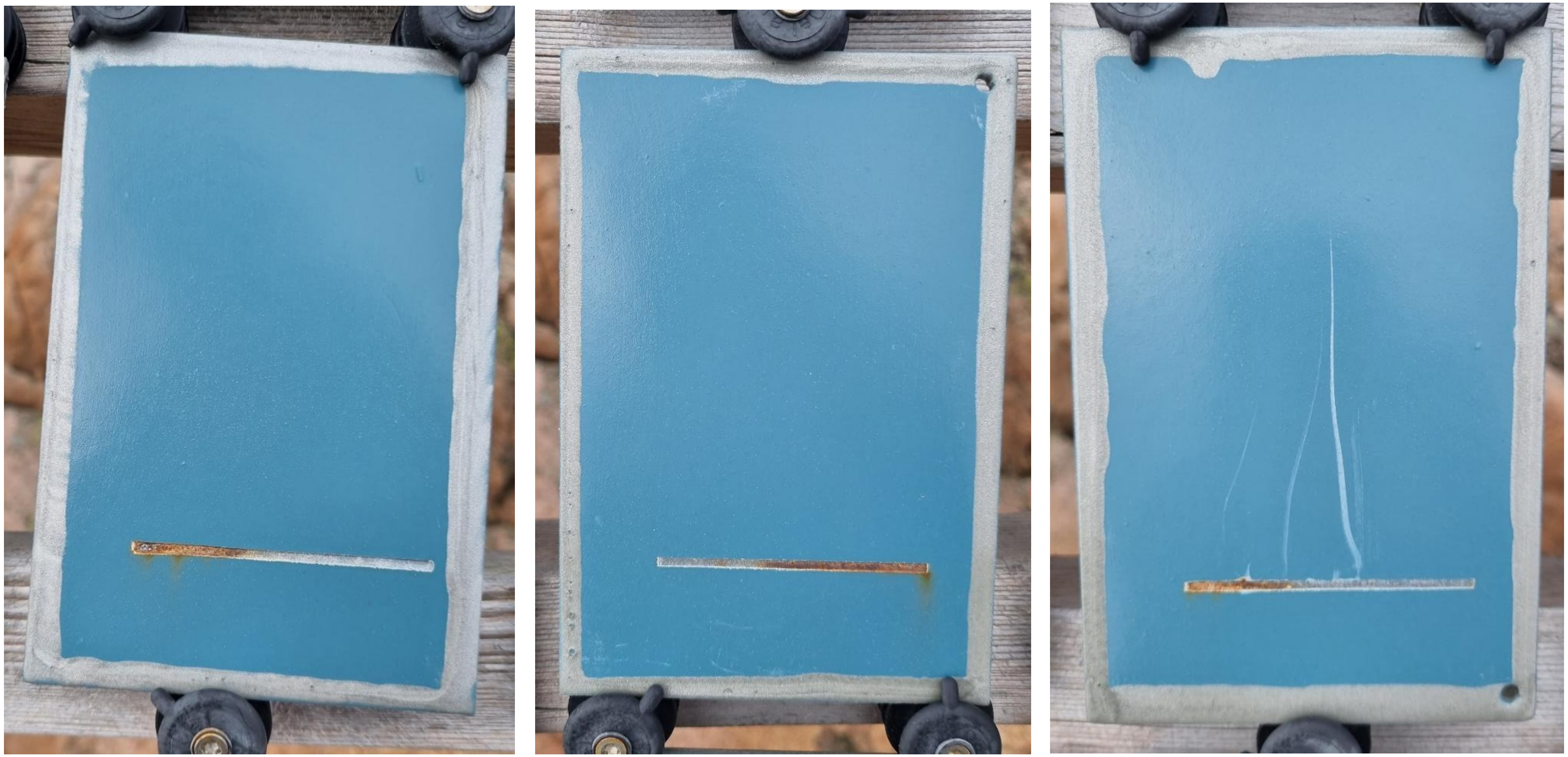

Figure 39 *System Q, bridge system, corresponding to system C5.08 according to SS-EN ISO 12944-5. EP (Zn 90%), EP (MIO), PUR.*

__Figure 40.__ System N, EP (Zn 90%)

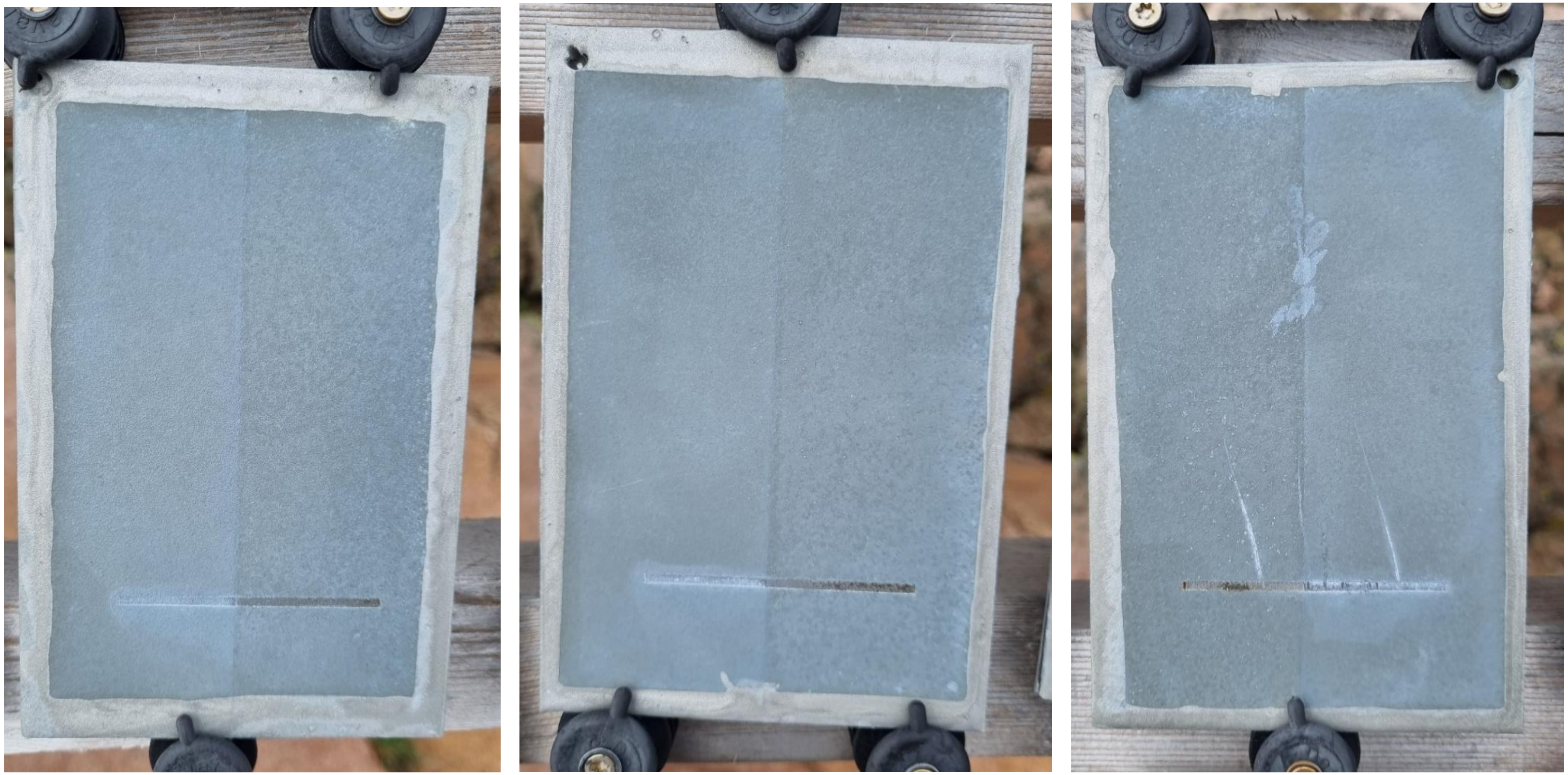

Figure 41 *System M, Fontezinc HR, Waterborne zinc silicate*

__Figure 42__ System U, Aqua Zinga, Waterborne zinc silicate

Figure 43 *System O, Zinc ethyl silicate, solvent borne silicate*

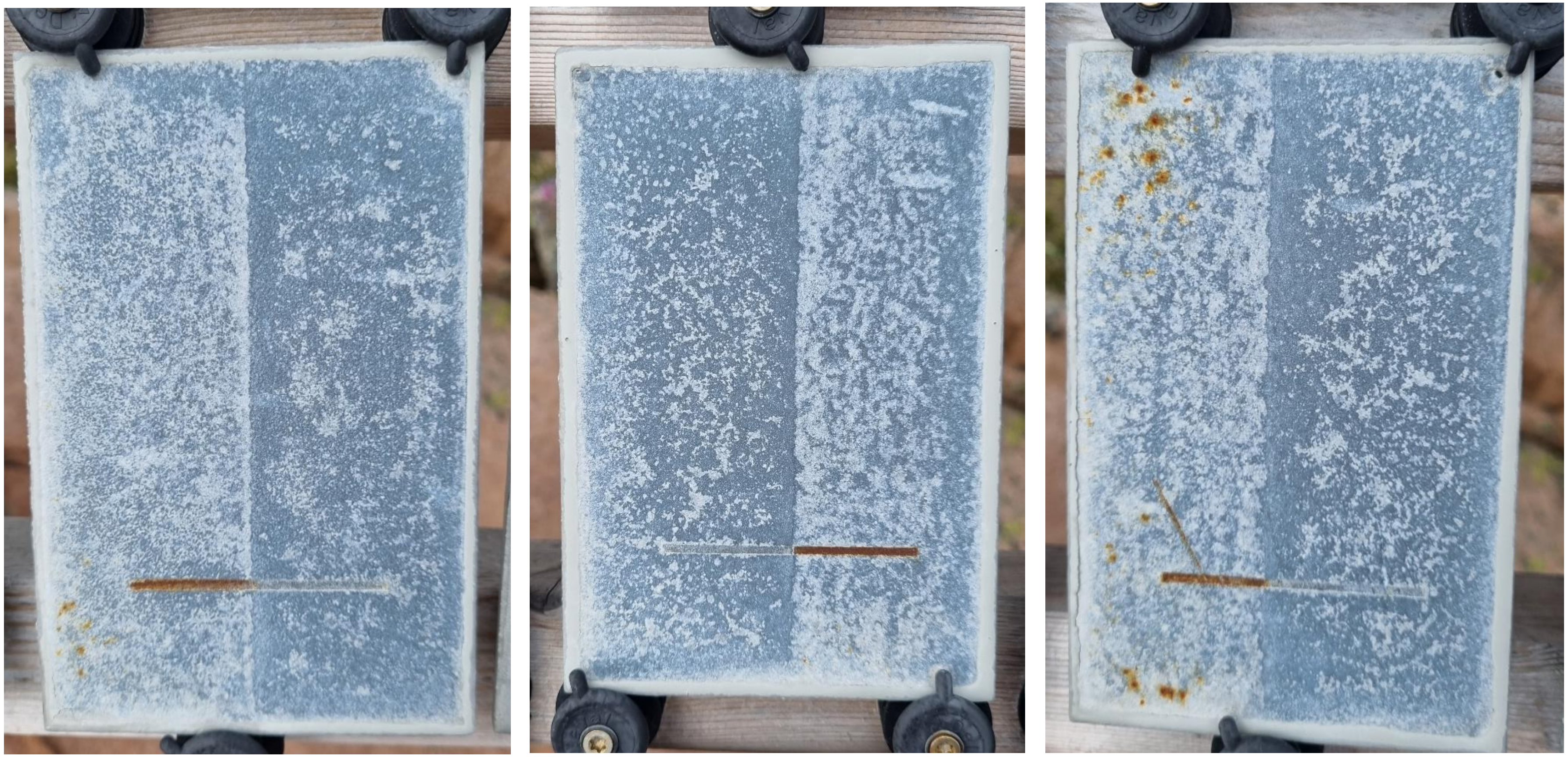

Figure 44 *system S, Zinga, one component zinc rich coating*

Figure 45 *System T. ZingAlu, Zinc/ Aluminum pigmented one component*

Figure 46 *System A, Fontezinc HR, laser*

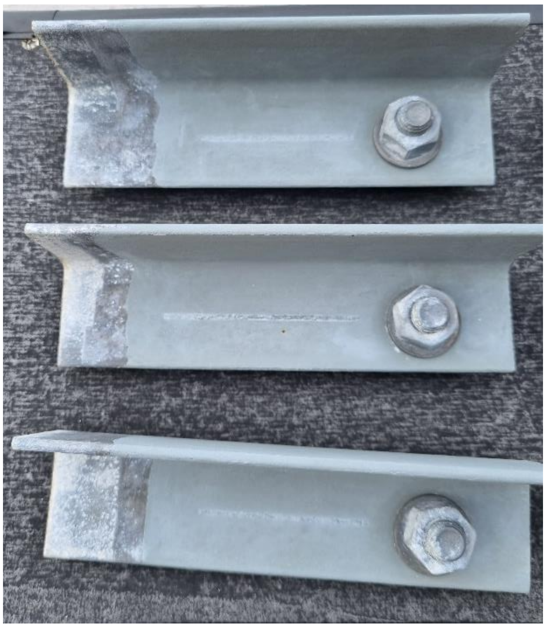

Figure 47 *System A, Fontezinc HR w scribe, laser*

Figure 48 *System E, Fontezinc HR, grinding*

Figure 49 *System E, Fontezinc HR with scribe, grinding*

Figure 50 *System G, Zn ESI, grinding*

Figure 51 *System C, Zn ESI, w scribe, grinding*

Figure 52 *System C, Zn ESI, laser*

Figure 53 *System C, Zn ESI w scribe laser*

Figure 54 System H, Biltema Zn spray, grinding

Figure 55 System H, Biltema Zn spray w scribe, grinding

Figure 56 System J, Zinga, grinding

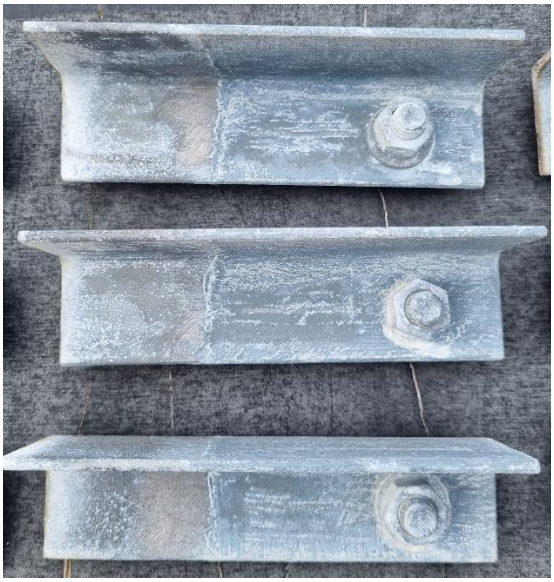

Figure 57 System J, Zinga with scribe, grindnig

Figure 58 *System K, Zinga, laser*

Figure 59 *System K, Zinga with scribe, laser*

Figure 60 *System F, Epoxy (Zn), grinding*

Figure 61 *System F, Epoxy (Zn) with scribe, grinding*

***Figure 62** System B, Epoxy (Zn), laser*

***Figure 63** System B, Epoxy (Zn) with scribe, laser*

***Figure 64** System I, bridge system, grinding*

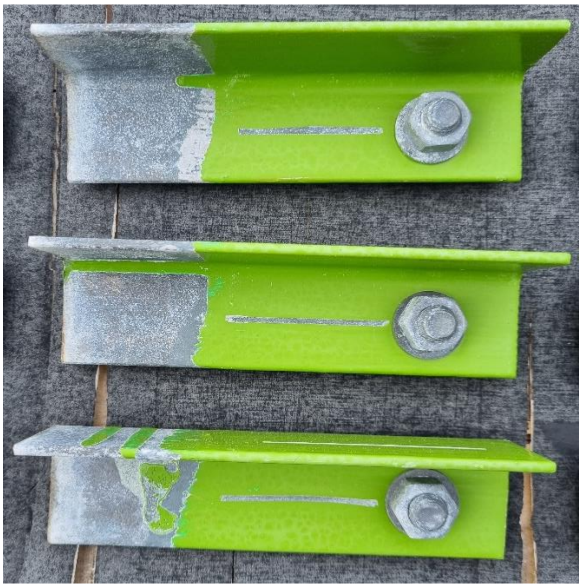

***Figure 65** System I, bridge system with scribe, grinding*

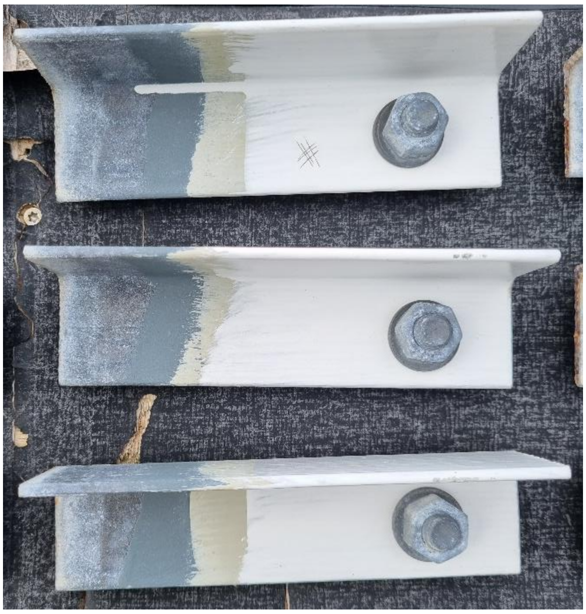

Figure 66 *System D, bridge system, laser*

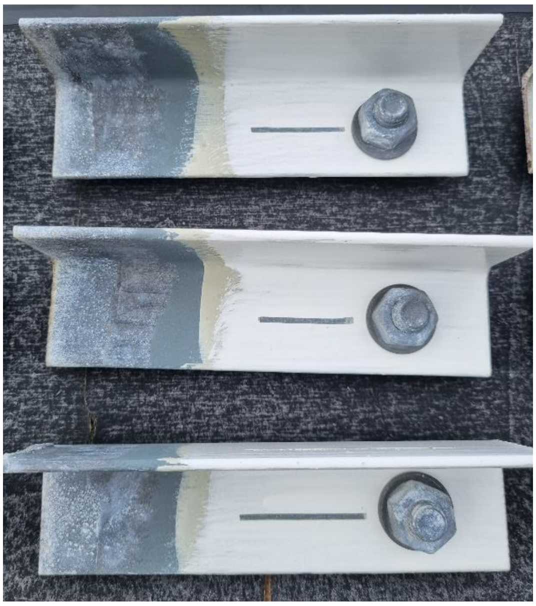

Figure 67 *System D, bridge system with scribe, laser*

Figure 68 *System L, Induragard, no pretreatment*

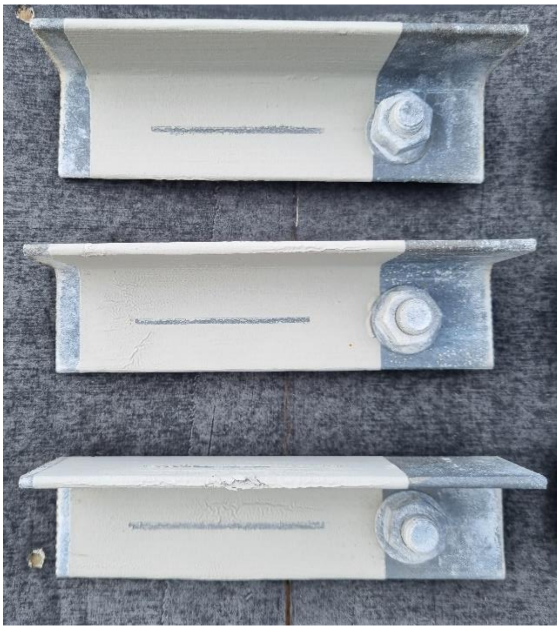

Figure 69 *System L, Induragard with scribe, no pretreatment*

RISE Research Institutes of Sweden AB
Box 857, 501 15 BORÅS, SWEDEN
Telephone: +46 10-516 50 00
E-mail: info@ri.se, Internet: www.ri.se

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Signerande parter

Andrew Gordon (AG)
RISE Research Institutes of Sweden AB
Org. nr 556464-6874
andrew.gordon@ri.se
+46 10 228 48 55
Signerade 2023-05-30 11:11:30 CEST (+0200)

Bjorn Tidbeck (BT)
bjorn.tidbeck@ri.se
Signerade 2023-05-30 12:33:01 CEST (+0200)